Lunar Regolith Simulant Materials: Recommendations for Standardization, Production and Usage

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We must continually set goals to challenge the human spirit to the utmost.

Wernher von Braun, 1967
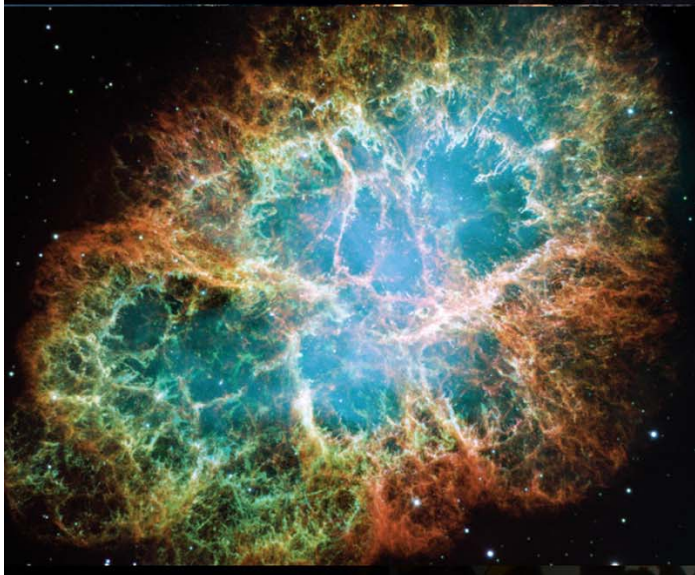
For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled.

Richard P. Feynman
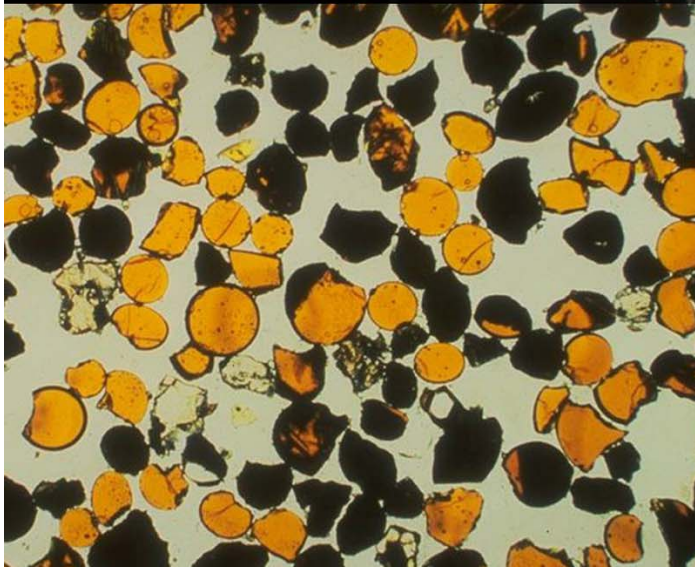
Unfortunately, soils are made by nature and not by man, and the products of nature are always complex.

Karl von Terzaghi, 1936

EXECUTIVE SUMMARY

Background

Lunar regolith is a mixture of rock, mineral and glass fragments transformed into a distinctive material by a unique combination of space weathering processes. It makes up the lunar soil that covers the surface of the Moon in thicknesses from centimeters to hundreds of meters; it reflects the geological differences observed in the lunar geography but also displays a remarkable uniformity in many physical characteristics. As NASA prepares to return humans to the lunar surface for a long-term presence, our knowledge of the lunar materials and their environment has been multiplied by the careful study of the lunar samples returned by the Apollo missions that represent a diversity of geological materials and processes. That critical knowledge, while still limited, enables us to define the Standard Lunar Regolith Simulant (SLRS) materials that should be used as lunar soil analogs in hardware development and testing.

The Apollo program developed a set of standard lunar soil simulants to test all surface systems in preparation for the lunar landings. This approach was highly successful despite the limited knowledge of the lunar surface at the time. These materials no longer exist and the library of documents describing their compositions is incomplete.

Although a variety of simulant materials was used to test Apollo surface systems, astronauts and mission controllers encountered several challenging problems. Some of the problems encountered with the lunar regolith resulted in:

a. Lunar Roving Vehicle (LRV) slippage and crew sinkage in steep slopes of loose regolith at crater edges.
b. Inability and persisting difficulty to penetrate lunar regolith with tools beyond tens of centimeters (core drilling tube, anchoring rods, and severe abrasion during excavation).
c. Lunar dust caused hardware failures:
    - Failure of seals on all rock-boxes sealed in their original vacuum (10^{-12} Torr) on the Moon, resulting in no lunar samples returned to Earth in pristine condition.
    - Dust jamming of extension tool handles.
    - Severe abrasion by lunar dust compromised the joints on Extra Vehicular Activity (EVA) suits resulting in pressure degradation and reduction in mobility.
   - Unforeseen dust accumulation on the LRV radiators required extensive astronaut time for unplanned cleaning tasks that proved ineffective.
d. Accumulation of lunar soil particles on EVA suits resulted in dust invasion of the lunar module and problems with reassembly of suits for subsequent EVAs.
e. Astronaut exposure to airborne dust causing physiological irritation.

The Apollo experience demonstrated the need for extensive testing of surface systems with materials similar to the in situ lunar materials that will be encountered. The Mars rovers

have experienced operational challenges in climbing slopes of loose soil that have required real-time problem simulation in a test-bed utilizing simulant material. As NASA considers a return to the Moon, the pressing need for SLRS materials is further compounded by the fact that the remaining lunar sample inventory currently available (~350 kg) is insufficient in quantity to support lunar technology projects and its scientific value is too great to be consumed by destructive studies. Every effort must be made to utilize simulants.

The 2005 Lunar Regolith Simulant Materials Workshop

The Lunar Regolith Simulant Materials Workshop was held in Huntsville, AL, on January 24-26, 2005, and was hosted by the Marshall Space Flight Center (MSFC). The sponsors of this workshop were the Exploration Systems Mission Directorate (ESMD), and the Marshall Space Flight Center in collaboration with the Johnson Space Center (JSC).

The purpose of the workshop was to identify the needs for widely-accepted, SLRS materials to perform research and development of technologies required for lunar operations and to establish a common, traceable, and repeatable process regarding the standardization, characterization, and distribution of lunar simulants for use by the scientific and engineering communities.

This workshop made extensive use of and endorsed many of the findings and recommendations of a 1989 workshop entitled "Workshop on Production and Uses of Simulated Lunar Materials." The work performed during the 2005 Workshop was focused to update the scientific and programmatic aspects of the material to reflect the current knowledge base and to best serve the current NASA program of lunar exploration.

The Lunar Regolith Simulant Materials Workshop was the first of four workshops that dealt with the topic in 2005 (Granular Materials in Lunar and Martian Exploration, Biological Effects of Lunar Dust, and Dust Mitigation Technologies Focus Group). Close collaboration between the various workshop organizing teams has yielded consensus on simulant requirements.

For further information, see the Lunar Regolith Simulant Materials Workshop website: http://est.msfc.nasa.gov/workshops/lrsm2005.html.

Lunar Simulant Materials

Lunar simulants were defined by the 1989 Workshop and the subsequent technical report published in 1991 (LPI Technical Report 91-01) as "*Any material manufactured from natural or synthetic terrestrial or meteoritic components for the purpose of simulating one or more physical and/or chemical properties of a lunar rock or soil.*" Terrestrial materials, specifically chosen to simulate the lunar regolith, need to be processed in order to replicate the critical physical and chemical parameters of the regolith; they may also have added synthetic materials such as glasses, metals, and minerals to provide some of the unique qualities of lunar regolith.

Simulants are needed for several exploration disciplines and each has special needs. For instance, l*unar resource simulants*, needed for studies of materials processing techniques, require very specific chemical and mineralogical similarity to lunar soils while geotechnical researchers require large volumes of materials that simulate physical behavior. *Lunar dust simulants*, needed for studies related to human toxicology, surface abrasion, and dust adhesion on system components, demand special processing to properly simulate the unique properties of the dust and achieve the required size fraction (<20 μm for human toxicology studies and <50 μm for systems testing).

The properties of lunar regolith simulants were a major topic of discussion during the 2005 Lunar Regolith Simulant Materials Workshop. A table of important regolith simulant properties was developed as part of the 2005 Workshop that reflects this discussion and the consensus of the participants. This table is presented in Appendix C.

Availability of Lunar Regolith Simulant Materials

Lunar simulants used in recent years are no longer produced and available supplies (e.g., JSC-1 and MLS-1) are insufficient to meet the needs of current lunar technology projects. Also, to our knowledge, lunar dust simulants have only been produced in very small quantities. Currently NASA does not have the simulants necessary to represent the diversity of material compositions expected to be encountered on the Moon (i.e., mare (basaltic), highland (anorthositic), rock-ice mixtures, etc). Testing of operational systems for future lunar missions, including polar missions, will require simulant compositions of the in situ materials expected to be found at each landing site.

A survey of potential users and estimates of needed simulant reserves, in the spring of 2005, indicated that the need for lunar simulant materials could fall between 125 and 250 metric tons over the next four years.

Selection of Standard Simulant Materials

Traceable standards are required for comparative testing and equipment qualification. Currently, no inter-laboratory SLRS materials or standard Mars regolith simulants have been developed by consensus of the scientific and engineering communities, leaving research and development efforts to rely on a wide variety of materials thus leading to data of questionable validity and applicability. Published results on In Situ Resource Utilization (ISRU) processes have demonstrated that the use of geologically inappropriate and poorly characterized simulant materials has yielded inconsistent and sometimes unverifiable results, as well as erroneous conclusions about the actual lunar regolith.

The performance of candidate technologies for surface operations can only be properly evaluated and compared by using common standard simulant materials. The use of these standard materials will significantly reduce development costs and risks by avoiding system design failures related to the use of improperly developed and/or maintained simulant materials. Dust simulants that are properly produced and standardized using defined

requirements will be critical to the understanding of the effects of dust on mission critical subsystems (e.g., life support, mobility systems, EVA suits) and humans.

The problems associated with the improper selection of simulant materials are further discussed in Section 4.0, Lunar Simulant Materials: Historical Development, Present Status, and Future Needs.

2005 Workshop Key Findings, Risk Mitigation and Recommendations

The 2005 Workshop utilized presentations, breakout sessions, and electronic capture of comments from the diverse community of experts present. From this material, key workshop findings were developed, risk mitigation strategies identified, and recommendations set forth. Key findings constitute the core of this report. Risk mitigation strategies and recommendations of the 2005 Workshop can be found in Section 5.0, Recommendation 1: Standard Lunar Regolith Simulant Materials, Section 6.0, Recommendation 2: Establish a Process for Development, Production, and Certification of Standard Lunar Regolith Simulant Materials, and Section 7.0, Recommendation 3: Develop a Long-Term Simulant Acquisition Strategy. A summary of the key recommendations follows.

2005 Workshop Recommendations

Workshop Recommendation 1 - Establish a common set of standards for simulant materials, known as SLRS, for NASA sponsored projects.

Standards should be based on the concepts of *family*, *roots*, and *derivatives*. New simulants should be based on the expected landing sites, including the lunar mare, highland and polar regions. This recommendation is further defined in Section 5.0, Recommendation 1: Standard Lunar Regolith Simulant Materials.

Workshop Recommendation 2 - Establish a process for the development, production and certification of SLRS materials. NASA should also proceed as quickly as practical with the development of requirements, standardization, and characterization of a family of simulants. This recommendation is further defined in Section 6.0, Recommendation 2: Establish a Process for Development, Production, and Certification of Standard Lunar Regolith Simulant Materials. An illustration of the process is displayed on the following page.

Workshop Recommendation 3 - Develop a long-term simulant acquisition strategy.

A Simulant Science Advisory Committee (SSAC) should be established to assist NASA in the development of requirements and the standardization of simulant materials. This committee should include, but not be limited to, members with expertise in planetary science (Moon, Mars, asteroids, etc.), development of geochemical standard reference materials, and materials science. This committee should meet as needed to perform its functions and issue its recommendations to NASA.

Simulant Requirements
- Focus Groups
- Regolith Properties
- Documents

Review/Advise

Propose

Development of simulant additive components
- Research Grants
- Focus: Experimental Production of Additives
- Additives: Agglutinates, Dust Fraction, Nanophase Fe

Curation/Distribution of SLRS Materials
- Packaging
- Storage Conditions
- Distribution/Ordering /Shipping

Manage

Geological materials purveyors

Submit

Additive simulants purveyors

Submit

Develop/Manage

Research Reports

Manage

Industry/ Contractor

Candidate Simulant Materials
- Characterization
- Summary Data Document
- Analog Field Test Sites Data

Review/Advise

Propose

Simulant Science Advisory Committee
- Knowledge base for NASA

Advise

Manage

Certification of SLRS Materials
- Sampling
- Batch Characterization

Manage

Characterization

NASA
Marshall Space Flight Center

Propose

NASA Policies
- Storage Curation
- Distribution/Handling /Usage
- Outreach/Education

Characterization

MSFC USGS other labs

Draft

Characterization

MSFC USGS other labs

Recommended
- Materials
- Mining Sites
- Processing

Draft Policies

NASA Management
- Approve

Develop

Manage

SLRS Materials Specification Design Document
- Source Location
- Modal Composition
- Chemical Composition (includes trace elements)
- Physical Characterization (size, dist., shape)

Spec's

Procurement of SLRS Materials
- Statement of Work (SOW)
- Request for Proposal
- Provider Selection and Management

Acquisition and Certification of Standard Lunar Regolith Simulant Materials.
This illustration depicts the role of MSFC in coordinating the multiple tasks required to make SLRS materials available to NASA-sponsored projects. The important roles of MSFC partners in this effort are also identified.

NASA should also develop policies related to the organization, procurement, quality control, certification, storage, distribution, and usage of simulant materials for NASA sponsored projects.

Additional information concerning policy and the functions of the Simulant Science Advisory Committee is further defined in Section 7.0, Recommendation 3: Develop a Long-Term Simulant Acquisition Strategy.

Workshop Recommendation 4 – Proceed as quickly as possible with a unified, near-term ESMD simulant acquisition through an immediate redeployment of lunar mare simulant JSC-1.

In response to the immediate needs for an adequate lunar regolith simulant by many NASA-funded technology projects and a larger science and engineering community, and in recognition of the value of (now exhausted) simulant JSC-1, NASA should immediately initiate a production run of JSC-1, a glass-rich basaltic ash prepared to approximate lunar mare soils of mid-range titanium content in order to provide simulant that is of general use to the community. This simulant should be used for short-term needs and to supplement the family of root simulants proposed for development as part of an overall simulant development and production plan.

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1.0   2005 LUNAR REGOLITH SIMULANT MATERIALS WORKSHOP

1.1   Purpose

The Lunar Regolith Simulant Materials Workshop was hosted by the Exploration Science and Technology Division at the Marshall Space Flight Center (MSFC) in Huntsville, AL, on January 24-26, 2005, and was sponsored by the Exploration Systems Mission Directorate (ESMD) and MSFC in collaboration with Johnson Space Center (JSC).

The goal of the Lunar Regolith Simulant Materials Workshop (hereafter referred to as the 2005 Workshop) was to establish requirements for the production and distribution of terrestrial analogs of lunar regolith, which will become the accepted source material standards for research and development efforts on space resources utilization technologies. The required degree of fidelity with which simulant materials must approximate the lunar regolith is higher for the development and validation of space resources utilization technologies than for any other technologies since space resources utilization hardware must be designed to handle, transport, and transform lunar materials. The availability of such simulant materials will undoubtedly benefit all technology development efforts conducted to realize NASA's plans for lunar surface operations. The current lack of available and commonly accepted simulant materials hampers research progress and often renders studies and performance comparisons of technologies inconclusive.

The workshop brought together over 90 attendees representing a wide range of expertise: lunar science experts, ESMD principal investigators, space and terrestrial systems engineers, and experts in simulant development, space resources utilization, and the physiological effects of dust particles. Also attending were Extra Vehicular Activity (EVA) and spacecraft life support technologists and NASA Headquarters managers. This very diverse group included representatives of science and engineering academia, mining and earth-moving equipment industries, aerospace industries, U.S. Army Cold Regions Research Laboratory, U.S. Geological Survey (USGS), and NASA, and provided a platform for broad discussion and requirements collection.

1.2   1989 Workshop on Production and Uses of Simulated Lunar Materials

On September 25-27, 1989, a workshop entitled "Workshop on Production and Uses of Simulated Lunar Materials" (hereafter referred to as the 1989 Workshop) was convened at the Lunar and Planetary Institute (LPI) in Houston, Texas, by David McKay and James Blacic. The purpose of this workshop was to define the need for simulated lunar materials and examine related issues in support of extended space exploration and development. The workshop focused on a detailed examination of the variety of potential simulants and the methods for their production, as well as policy issues that were pertinent at the time. The subsequent workshop report was published in 1991 as LPI Technical Report 91-01 (*McKay et al.*, 1991).

The 2005 Workshop made extensive use of and endorsed many of the findings and recommendations of the 1989 Workshop, and several experts who participated in that event were

invited to the 2005 Workshop. The work performed during the 2005 Workshop was focused on updating the scientific and programmatic aspects of the material to reflect the current knowledge base.

A summary of the findings and recommendations of the 1989 Workshop is provided in Appendix C of this report.

1.3   2005 Lunar Regolith Simulant Materials Workshop Agenda and Data Collection

The 2005 Workshop was structured into two activities. The first activity was a set of presentations chosen to cover the issues facing the development of simulant materials and to promote a thorough discussion among the attendees prior to the working sessions. The titles of the presentations are listed below:

- The Status of Lunar Simulant Materials (L. Sibille)

- Physical and Chemical Characteristics of Lunar Regolith: Considerations for Simulants (L. A. Taylor)

- Evolution of the Lunar Regolith (D. S. McKay)

- The Geotechnical Properties of the Lunar Regolith: From Equator to the Poles (L. A. Taylor)

- Lunar Regolith Simulant MLS-1: Production and Engineering Properties (S. Batiste)

- Characterization Strategies and Requirements for Lunar Regolith Simulant Materials (P. K. Carpenter)

- New Lunar Root Simulants: JSC-2 (JSC-1 Clone) and JSC-3 (J. L. Carter)

- Characterization of Chemical and Physical Properties of Proposed Simulant Materials (G. P. Meeker)

- Development of Geochemical Reference Materials at the United States Geological Survey (S. A. Wilson)

- The Moon as a Beach of Fine Powders (M. Nakagawa)

- Biological Effects of Lunar Surface Mineral Particulates (R. Kerschmann)

- The Effects of Lunar Dust on Advanced EVA Systems: Lessons from Apollo (R.A. Creel)

- Sintering, Melting, and Crystallization of Lunar Soil With An Experimental Petrologic Point of View (G. E. Lofgren)

- Towards Lunar Simulants Possessing Properties Critical to Research & Development of Extractive Processes (D. Sadoway)

- The In-Situ State: The Elusive Ingredient in Lunar Simulant (E. S. Berney)

- Lunar Regolith Simulant Requirements: Mechanical Properties Considerations (D. M. Cole)

- Composition of the Lunar Highland Crust: A New Model (P. D. Lowman)

- Space Radiation and Lunar Regolith (J. H. Adams)

A compilation of the abstracts of all presentations and additional posters is available on the workshop website at http://est.msfc.nasa.gov/workshops/lrsm2005.html.

The second activity consisted of a working session focused on the gathering of requirements for lunar simulant materials. Topic experts were invited to participate in one of three working groups that most closely matched their areas of interest and expertise. This activity was split into three subject expert groups, which covered the physical, chemical and dust characteristics of the required lunar simulant. Participants were asked to evaluate the importance of reproducing specific known physical and chemical properties of the lunar regolith, as they would affect the performance of potential technologies developed for lunar surface operations. Three expert groups were formed to examine lunar activities involving physical handling and processing of the regolith, chemical processing of the regolith, and those activities affected by the dust fraction of the regolith (i.e. grain size below 50 μm). Early recognition of the specific problems caused by the dust fraction of the regolith directed us to assign an expert group to that issue. The resulting ranking and written evaluations were used to populate a Properties Requirements Matrix (PRM). Comments and requirements were captured utilizing a server-based collaboration tool and electronic data capture. Data collected during these sessions was analyzed and used to generate this report, and prepare the requirements document for Standard Lunar Regolith Simulant (SLRS) materials, which will be published separately.

The relation of the 2005 Workshop to the requirements gathering process is illustrated in Figure 1.1.
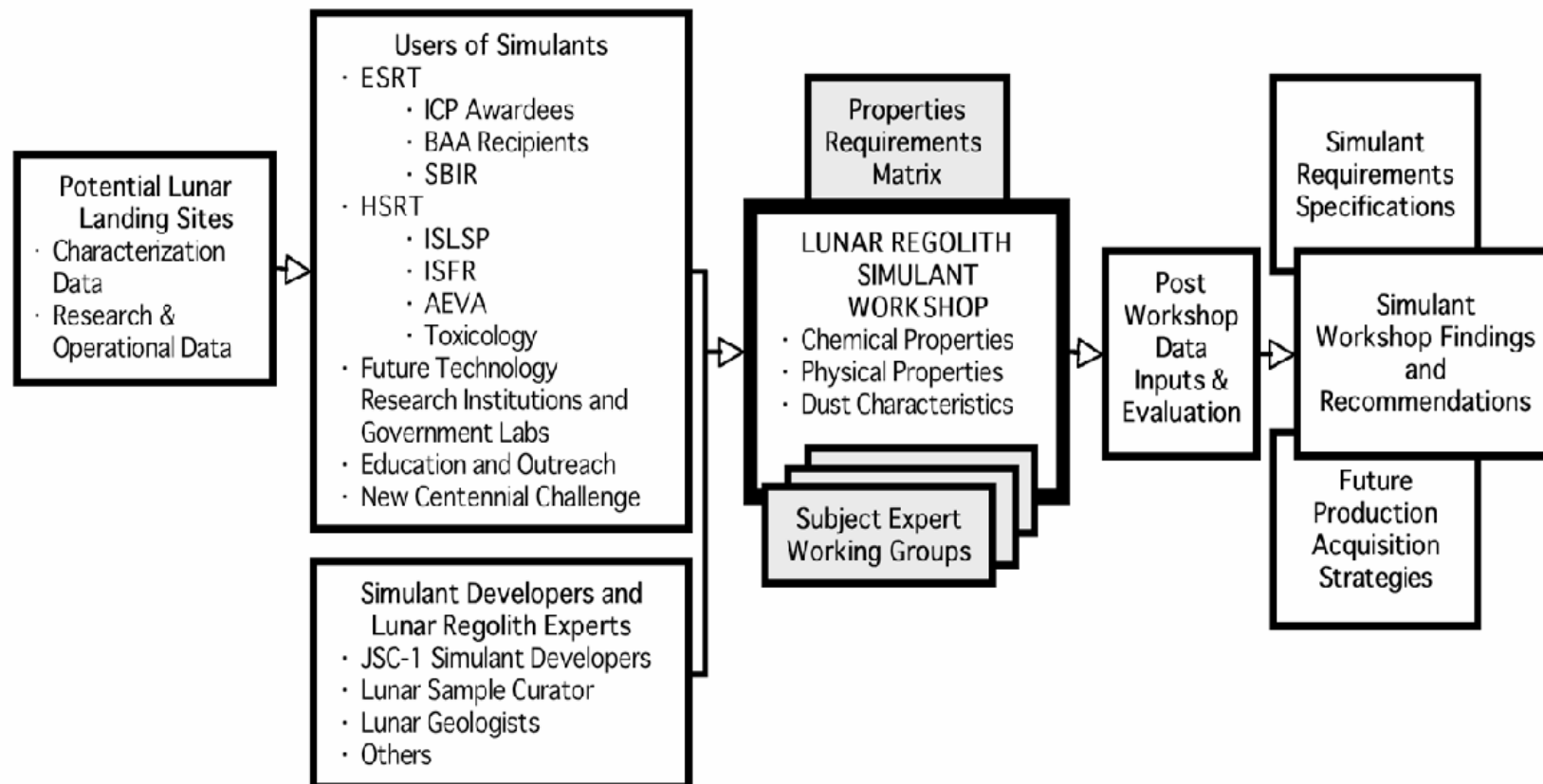
Figure 1.1 Simulant Requirements Definition, 2005 Workshop Findings, and Recommendations Process

2.0 LUNAR REGOLITH SIMULANT MATERIAL NEEDS

2.1 Introduction

Lunar samples returned from the Apollo missions represent diverse geological materials and processes, and have been studied in considerable detail using numerous characterization techniques. Developing lunar simulants presents a challenge in matching terrestrial materials to lunar soils and rocks. Existing lunar simulants such as JSC-1 and MLS-1 have been utilized as engineering test materials with primary emphasis placed on determining geotechnical properties and secondary emphasis on supporting chemical and mineralogical analysis. Implementation of a comprehensive suite of SLRS materials for use in the development of all surface technologies for lunar operations will require a diverse set of mineral, rock, and synthetic materials, coupled with processing technologies and characterization by both geotechnical and chemical/mineralogical techniques. Presented here is a brief roadmap coupled with development requirements for lunar simulants that support anticipated NASA missions.

Lunar soils are comprised of materials that are predominantly basaltic and anorthositic, reflecting mare and highland source regions, respectively. Meteorite impact events have mixed these materials over large areas, and have produced significant fragmentation, melting, and glass formation. These actions are evidenced in the texture, chemistry, mineralogy, and presence of significant glass fraction as well as vapor-deposited reduced iron. Lunar simulants can, in principle, be matched to lunar source materials by means of selecting root components that, when mixed and processed appropriately, duplicate the characteristics of the lunar target materials. Potential root simulants are basalt, anorthosite, mineral and glass separates, and size-fractions such as dust and Fe nanophase material. Meteoritic material clearly exists in lunar soils based on trace element chemistry, but also represents a challenge in identifying equivalent terrestrial materials to use as meteorite simulants. Quantitative modeling of root simulant materials to match Apollo soil chemistry can be performed by choosing sets of simulants, then determining a least-squares fit to the Apollo bulk chemistry and iterating the mix proportions. One primary goal of this workshop was to determine which lunar regolith materials need to be simulated, and the accuracy with which the simulant needs to match the target lunar material.

2.2 Lunar Exploration Architecture

A clear definition of the lunar exploration architecture is needed to give technology systems developers and researchers the proper framework within which they can create the technologies and surface systems required to enable the Vision for Space Exploration. Research and development of required lunar operations technologies rely on decisions such as the choice of lunar landing sites, the short-term and long-term objectives of a human presence on the Moon, and the studies that must be conducted on the lunar surface to provide experience in preparation for human missions to Mars. These decisions will affect our selection of the types and quantities of lunar simulant materials that are required to support the overall exploration effort.

At the time of this publication, the authors are aware that the range of human and robotic activities taking place during lunar surface missions has yet to be defined as part of an accepted architecture of the lunar exploration effort. The following paragraphs describe the functional

elements expected to be part of such exploration architecture. These descriptions are based on the Vision for Space Exploration (February, 2004) and recommendations and guidelines of recently published NASA documents, such as the Exploration System of Systems Technical Requirements Document (*Lembeck*, 2005), and the Robotic Lunar Exploration Program (RLEP) Requirements Document (*Trosper*, 2005). Reports of NASA-appointed study teams such as the Lunar Exploration Analysis Group (LEAG) and the Exploration Systems Architecture Study (ESAS) team have also been consulted (*Taylor, G.*, 2005; *Spudis*, 2005).

2.3 Lunar Exploration Systems Requirements

NASA's return to the Moon is part of the larger framework of a sustained and affordable space exploration architecture that will extend the human presence across the solar system. The lunar missions will pursue three main objectives: advance scientific knowledge of the solar system and the universe through exploration of the lunar environment and geology, learn to identify and use in situ resources to sustain human missions to the planets, and acquire operational experience on the lunar surface to prepare for human missions to Mars and beyond. The RLEP plans to accomplish several robotic missions in lunar orbit and to the lunar surface as precursors to human landings. The Lunar Reconnaissance Orbiter (LRO) will be the first of these precursor missions to be launched in 2008 to map the lunar surface and subsurface to advance lunar science, identify mineral resources, and characterize the surface environment for future landings by orbital remote sensing. Such global mapping will enable the selection of safe landing sites for human short-duration and outpost missions. The presence of resources of high interest, such as polar water ice in permanently shadowed areas or oxygen-bearing minerals will be confirmed and quantified by acquisition of in situ ground truth data using robotic landers and rovers. These unmanned missions may also be used to support later human missions by deploying communications/navigation, power and other infrastructure. The extraction and transformation of confirmed in situ resources will first be demonstrated at small scale to validate technologies before their use as part of long-duration stays on the lunar surface. This may lead to requirements for larger scale resource extraction and processing if determined to be economically beneficial and to result in accrued mission safety. These requirements include but are not limited to the excavation of surface materials for radiation shielding, production of propellants and life support gases, and the production of materials for human habitation.

The successful realization of such an infrastructure on the lunar surface will rely on the performance of a range of specialized systems capable of operating for long periods of time in the extreme lunar conditions. Many surface systems will face the challenges of dealing with the lunar regolith in unprecedented ways, including surface traversing (rovers, hoppers), drilling, excavating, crushing and transporting of regolith, introducing regolith into chemical processors, and mitigating dust accumulation. These technical challenges are made more formidable by the lunar environment; low gravity (1/6 g), low vacuum (10^{-12} Torr), very wide temperature ranges (-230 °C to +120 °C), and alternating 14 Earth day-long nights and days. While the challenges are great, these capabilities will also make possible the extraction of materials for in situ habitat construction and repair and fabrication of energy-producing devices from lunar materials. Such a sophisticated infrastructure would be essential to realize a truly sustainable space exploration architecture.

The Moon will become a test bed for systems to be used in the exploration and human habitation of the martian surface. Systems will be deployed on the lunar surface to practice the techniques required by autonomous and manned systems to be used later on Mars. Operational experience and validation of technologies in the lunar environment will be sought to reduce risks for missions to Mars.

2.4   Simulant Material Needs in Research and Technology Development

Plans to excavate raw materials, extract in situ resources to manufacture products for use on the Moon or for export to in-space destinations, and the establishing of ambitious scientific installations such as advanced astronomical observatories on the lunar surface, demand that extensive testing be performed with materials that are as close as possible to the regolith that will be encountered. The need for simulant materials cannot be overstated.

For any successful mission, a set of current and sometimes new supporting technologies must be provided. The performance of current technologies must be assessed against a common set of criteria to allow the system designer to make intelligent choices when selecting high value, low risk systems. Technology gaps that appear between requirements and current technologies must be identified and new technologies developed. Subsequently, the critical phases of research and engineering lead to new concepts being formulated and promising technologies selected for further maturation. As new concepts develop and emerge beyond basic research, they will be demonstrated in the laboratory and then transferred to the engineer for further development into working ground and flight hardware.

During operations on planetary surfaces, the performance of these technologies will depend on the physical and chemical properties of lunar and martian materials upon which surface systems will be operated. Observations and sampling of surface and subsurface materials by robotic payloads and humans will help the mission designer understand the relationship between variations in regolith properties and efficiency of the deployed systems.

Given the complex nature of lunar materials and their diversity across the different regions with respect to mineralogy, chemical compositions, maturity and local environmental effects, it is not possible to define a single material to serve as simulant for all lunar regolith materials. However, the present state of knowledge of lunar geological history and the physical evidence provided by the lunar samples collected allow experts to discern the major characteristics of the lunar regolith depending upon region of origin and local environment. Such crucial knowledge enables us to estimate that a number between five and 10 simulant materials would be adequate to meet the requirements for proper technology development and testing for lunar surface mission systems.

The lunar regions visited by the Apollo missions and the robotic Luna landers are best known and provide benchmarks for simulant materials development. However, these sites represent a small fraction of the lunar surface and are not necessarily representative of other significant regions, such as the lunar highlands, lunar poles, and permanently illuminated or shadowed areas, where the local environment factors are unique to these localities. The definition of high fidelity simulant materials for the regolith found in these regions will only be possible based on analysis of samples from these areas. In the meantime, the development of simulant materials needed for technologies destined to operate in such poorly known lunar regions will rely on

approximations and interpretations of remote-sensing data. The data that will be collected from future orbital missions such as the LRO and robotic landing missions to the lunar poles will enable the preparation of simulant materials that will be critically needed to prepare human missions to these areas.

In the end, the research and engineering development cycle for flight systems will require that engineers and scientists adhere to a strict set of standards in both the chosen methodologies and test materials. To properly select technologies that will operate and survive on the lunar and martian surface, scientists and engineers must account for the unique characteristics of the surface regolith and rocks that will be encountered. Challenges that occurred during the Apollo missions in maintaining the Lunar Roving Vehicle (LRV) and astronaut's EVA suits, equipment seals, and drilling equipment clearly illustrate the need for comprehensive testing of surface equipment with simulant materials that are a close approximation of the surface materials to be encountered.

2.5   Lunar Materials versus Terrestrial Simulant Materials

Lunar samples have been returned from the Moon by both the Luna and Apollo missions, and totaled approximately 380 kg of material, of which 350 kg are still available today. The lunar rock and soil collection primarily represents rock samples from the Apollo 11, 12, 14, 15, 16, and 17 mission sites. These missions have predominantly sampled material from lunar mare sites which were less cratered and presented the safest locations for landing and exploration. The Apollo 15 and 16 sites were positioned adjacent to highland terrain and came closest to sampling lunar highland material. The lunar samples reflect a more restricted geological environment on the Moon compared to the diversity of environments on Earth. It is generally thought that a catastrophic melting event resulted in formation of a lunar magma ocean, from which plagioclase feldspar floated to the surface and formed the anorthosite rock type of the lunar highlands. This scenario has historically been the subject of debate, but has been resolved based on extensive geological analysis. However, inspection of surface photographs at the Apollo 15 site have been interpreted to represent layering suggestive of finely interspersed basaltic lava flows (*Lowman*, 2005). The lunar mare basins were produced by eruption of basaltic lava from ring-shaped fractures due to large impact events.

This simple scenario, crustal rockbergs of anorthosite and impact basins filled with basalt, both modified by meteorite impact events, is certainly a drastic simplification, but is sufficient to summarize the major geological terrains on the Moon. By contrast, such a description would not be sufficient to describe Earth geological history. The lunar surface consisting of these mare and highland rocks has been subjected to a considerable, though early, meteorite impact history that has locally redistributed material and modified it by crushing and melting. Thus, the major weathering force on the Moon is due to impact events, with perhaps secondary influence from daily lunar earthquakes that have extensively fractured the bedrock. The Earth presents a diverse set of materials and processes that includes significant redistribution of rocks by the action of plate tectonics, and weathering forces that are significant due to the presence of water and wind. More specifically, lunar materials have formed from different source materials, equilibrated under more reducing conditions, and have been modified by impact processes. Terrestrial materials are typically formed under more oxidizing conditions. These differences are evidenced

in source rock chemistry and mineralogy, coupled with differences in geological processes and the absence of terrestrial weathering reactions on the Moon. The lunar sample inventory is compositionally more restricted than terrestrial materials. Due to the remarkable range of textural features exhibited by the samples, detailed scientific investigations have been required. A selection of lunar materials is presented in Figures 2.1 to 2.5.

The lunar sample inventory is priceless and its use in destructive testing is understandably very limited. The development of lunar simulants is logically supported by these facts, as the science and engineering communities require consumable rock and soil materials that must duplicate as many properties of the lunar regolith as is technically and economically feasible. This degree of duplication is referred to as the *fidelity* of the simulant. Our ability to develop high-fidelity simulants relies on correlating their characteristics and material behavior in Earth-based testing with that of actual lunar material. Such truth-based development can be achieved through granting access to lunar samples for use in engineering tests using small quantities, followed by application of scaling laws when possible. If such an approach is not a viable option, the use of data obtained during past lunar missions and new testing data on the lunar surface during upcoming precursor missions will be required. Simulants must be produced from terrestrial rock and mineral sources that approach those of lunar materials in terms of chemistry and mineralogy, as well as physical and geotechnical properties. The challenge is to identify terrestrial source materials for use in simulant development and to apply the programs of quality control that are normally used for production of standard reference materials, to produce a material that is inherently like that of the lunar regolith (i.e., a soil with variable characteristics). As will be discussed, the basic needs of the communities are to have access to a lunar mare simulant, a lunar highland simulant, and to develop other simulants that are more specifically adjusted for processing operations that warrant a higher fidelity.

The emphasis on the utilization of in situ mineral resources as part of establishing a human presence on the Moon and Mars places specific requirements on the development of simulants from terrestrial source materials and forces a close examination of the relationship between terrestrial simulant materials and lunar regolith materials. As an example of special interest, lunar mineralogical materials, enriched in certain elements, are the potential equivalents of terrestrial ore deposits. The Apollo 17 orange glass is such a material (Figures 2.4 and 2.5). This orange glass is thought to have formed from volcanic fire fountains, and contains elevated concentrations of titanium. Glassy source materials found in the regolith are attractive as a resource since re-melting glass in extractive processing requires less energy than is necessary to melt rocks or other minerals. Orbital imaging of the Moon has also revealed higher concentrations of Ti and Fe that are associated with the lunar mare. Renewed lunar exploration and resource exploitation will require improved knowledge of the locations enriched materials, and high resolution compositional mapping of the lunar surface will be a necessary part of missions that prepare for landings.

The development of resource processing techniques thus depends on the use of simulant materials that reflect regolith compositions commonly found on the moon as well as specific simulants that duplicate these enriched materials of importance. In addition to the need for mare basaltic and highland anorthositic simulants, it is clear that derivative simulants that duplicate glassy agglutinates and spherical orange glasses in lunar soils are important for the development of lunar ore processing technologies.
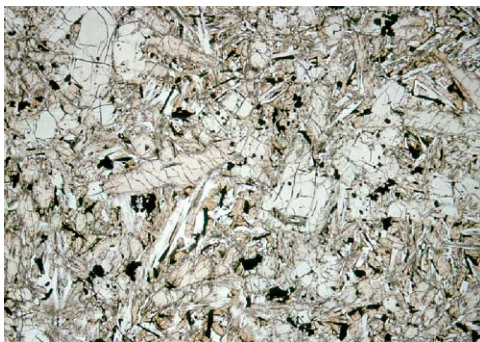
Olivine Basalt (Low Ti Basalt) 12002
20X, plane polarized light. Field of view 8 mm long dimension
This transmitted light photomicrograph shows an example of low-Ti mare basalt. Sample 12002, an Apollo 12 low-Ti basalt, contains red-brown pyroxene, colorless lath-shaped plagioclase, colorless blocky olivine, minor ilmenite, and chromite. The abundance of elongated pyroxene and plagioclase is indicative of rapid cooling.
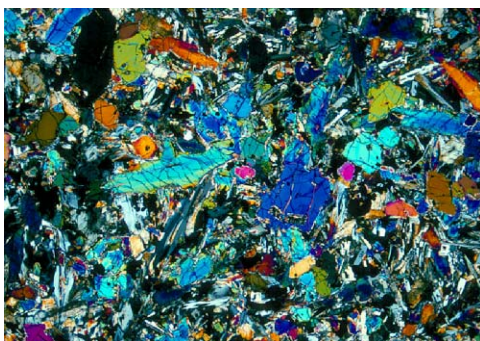
Olivine Basalt (Low Ti Basalt) 12002
20X, cross polarized light. Field of view 8 mm long dimension
The pyroxene in 12002 exhibits sector zoning from a pigeonite core to subcalcic-augite in one sector, and to ferropigeonite in the other sector. This zoning is in response to rapid cooling during crystal growth, and it is thought that this sample represents a primitive lunar liquid that originated at a depth of ~300 km.
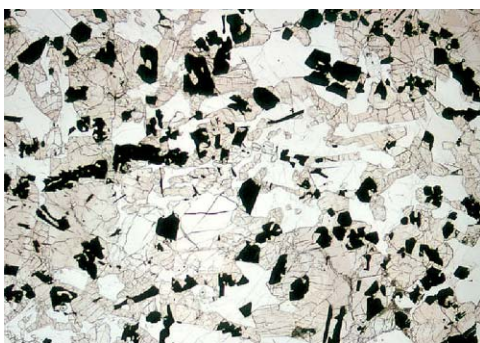
High Ti Basalt 70017
20X, plane polarized light. Field of view 8 mm long dimension
This is a high-Ti basalt from the Taurus-Littrow Apollo 17 site. Sample 70017 is a vesicular, medium-grained basalt, and contains abundant pyroxene, plagioclase, and Fe-Ti oxides that include ilmenite, ulvospinel, and armalcolite, with only minor olivine. The larger grain size compared to 12002 is indicative of slower cooling during crystallization. Ilmenite is abundant in this sample, and is responsible for the elevated Ti content. This was the last sample collected by the Apollo 17 astronauts and the final Apollo sample collected on the Moon.
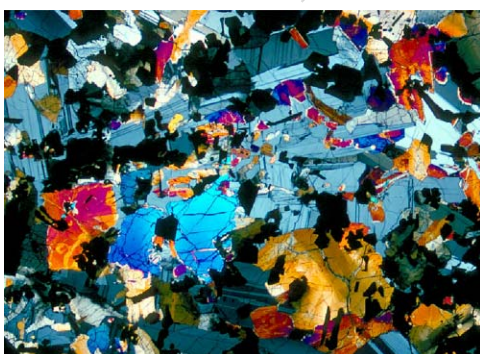
High Ti Basalt 70017
20X, cross polarized light. Field of view 8 mm long dimension
The pyroxenes in 70017 are zoned with augite cores that transition to pigeonite and Fe-rich rims. Plagioclase surrounds euhedral (faceted) pyroxene in a texture called *poikilitic*. This sample also exhibits evidence for silicate liquid immiscibility based on analysis of melt inclusions.

Figure 2.1 The Nature of Lunar Materials: Lunar Rocks I

LUNAR ROCKS
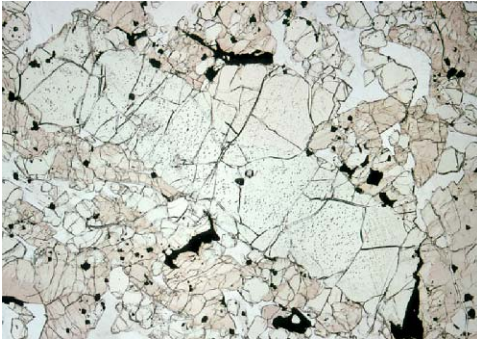
Ilmenite Olivine Basalt 12005
20X, plane polarized light. Field of view 8 mm long dimension
This ilmenite olivine basalt is a sample from the Apollo 12 site. Sample 12005 contains large green olivine crystals surrounded by red pyroxene and relatively minor ilmenite, which encloses olivine and pyroxene. It is grouped with ilmenite basalts despite having a relatively low TiO_2 content of 2.8 wt%. The olivine in 12005 has a high MgO content.
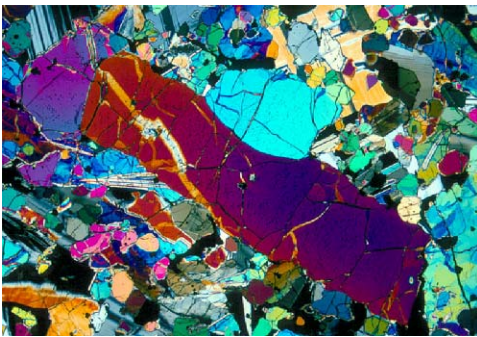
Ilmenite Olivine Basalt 12005
20X, cross polarized light. Field of view 8 mm long dimension
Sample 12005 is thought to be a lava lake cumulate from the lunar surface. The term *cumulate* means that settling, floating, or accumulation of crystals has occurred. It is very rich in olivine and pyroxene. Most of the larger oxides and plagioclase are interstitial, having grown in the intercumulus pore spaces. The two largest grains occupying the center are olivine crystals, with tiny, oriented arrays of trapped melt inclusions. Plagioclase is white and pyroxene is brown.
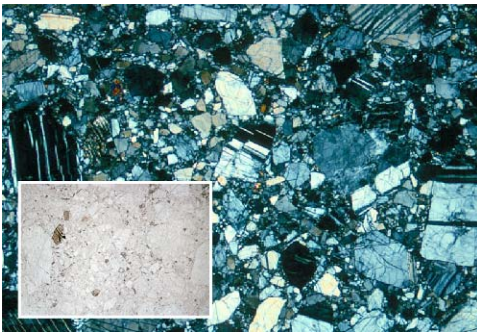
Ferroan Anorthosite 60025
20X, cross polarized light (Inset 20X, plane polarized light). Field of view 8 mm long dimension
Sample 60025 is a lunar highlands anorthosite from the Apollo 16 site. It is a cumulate that formed by floating of plagioclase in the lunar magma ocean during formation of the early lunar crust. Technically, it is a lithified anorthosite breccia or cataclastite, and contains ~98% plagioclase of composition An_{95} to An_{97}, and only 2% pyroxene. Fragments of several anorthosite compositions, as determined from the pyroxene compositions, are present. Pyroxenes include augite and orthopyroxene, and olivine is rare. Note the faulted plagioclase crystal (center) and numerous other deformed, faulted, and polygonized grains. All grain sizes exist as evidence of impact processes. Sample 60025 was determined to be 4.44 aeons old by Sm-Nd dating, which is about 110 million years younger than the age of the Moon.

Shocked Highland Norite 78235
40X, plane polarized light. Field of view 4 mm long dimension
Sample 78235 is a coarse-grained norite, probably a cumulate, of the lunar highland plutonic suite. It has undergone heavy shock metamorphism and exhibits impact melt veins quenched to glass, polygonized orthopyroxene, and plagioclase that has been partially converted to Maskelynite (a shock glass product) and, in some places, flow deformed. However, the original mineralogy and cumulate texture of the pristine parent material still exist. Highly fractured brown orthopyroxene is visible, as is plagioclase that has abundant exsolved oxide dust (gray).

Figure 2.2 The Nature of Lunar Materials: Lunar Rocks II

LUNAR BRECCIAS
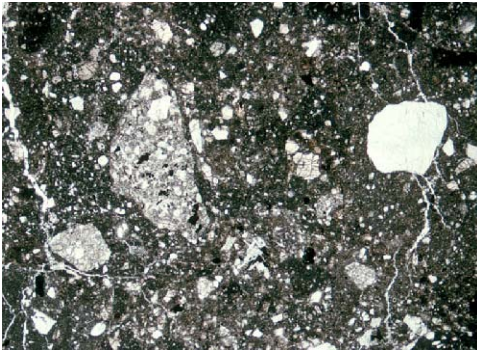
Polymict Breccia 14305
20X, plane polarized light. Field of view 8 mm long dimension
Sample 14305 is a polymict breccia from the Apollo 14 site, which exhibits rock and crystal fragments set in a dark matrix. The fragments include other breccias, and this polymict rock contains a variety of lithologies, chemistries, and histories. Several impact events are required to produce this mixing of rock types. The large light-colored fragment on the right is shocked anorthosite. The large grain to the left of center is a breccia clast, as is a smaller fragment to its lower left. A mare basalt clast from this sample was found to be of the advanced age of 4.23 aeons, and cosmic ray exposure studies have demonstrated that this sample was tumbled over time.
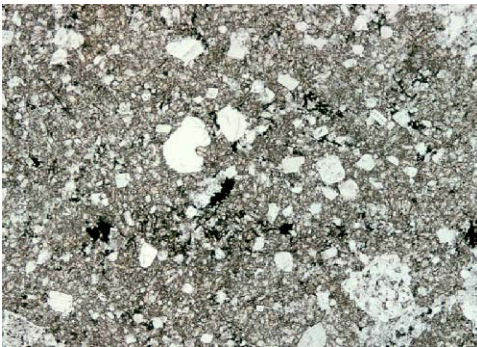
Impact Melt Breccia 65015
40X, plane polarized light. Field of view 4 mm long dimension
Sample 65015 is an impact melt breccia from the Apollo 16 site, which contains clasts of anorthosite, gabbroic anorthosite, and some basaltic material. It is interpreted to have formed from a melt sheet of fallback breccia inside a large lunar crater, which fell into a short-lived lava lake. The trace element chemistry of this sample is similar to KREEP basalts, and significant component of meteoritic materials is present based on the elevated Iridium content.

LUNAR REGOLITH

The famous footprint left by Neil A. Armstrong on July 20, 1969, in the lunar regolith is 2.5 cm deep. It demonstrates both the powdery nature and the apparent cohesion of the regolith, which mainly consist of particles ranging from sub-micron dimensions to 1 cm. The lunar regolith is mainly formed by the in-situ degradation of underlying rocks due to the incessant meteoritic bombardment of the lunar surface. Larger, less frequent impacts are able to excavate new bedrock while more numerous smaller ones mix and further break the existing material. After 4.4 aeons of such activity, the thickness of regolith is estimated to average 4 to 5 m in the mare areas and 10 to 15 m in older highland areas.

Regolith Breccia 15299
20X, plane polarized light. Field of view 8 mm long dimension
Sample 15299 is a regolith breccia from the Apollo 15 site, and shows a variety of rocks that include fragments of anorthosite, basalt, orange and green glass spheres and fragments (colorless, hard to distinguish), and monomineralic fragments in a dark brown glass matrix. Dark regions may be relict agglutinates, which distinguish this material as a regolith breccia. This breccia represents the total package of regolith materials that are shown in disaggregated form in the following images.

Figure 2.3 The Nature of Lunar Materials: Lunar Breccias and Regolith

LUNAR REGOLITH
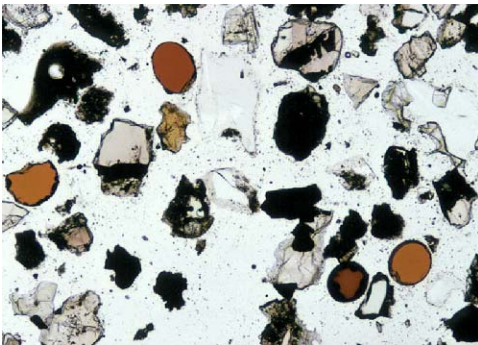
Mare Regolith 70181
100X, plane polarized light. Field of view 1.6 mm long dimension
Sample 70181 is a mare regolith from the Apollo 17 site. Most of this soil is derived from high-Ti mare basalts, and includes light purple-brown pyroxenes, colorless plagioclase, basalt rock fragments, orange glass spheres (fire fountain droplets), and Fe-Ti oxides (black grain below center). Many of the dark fragments are devitrified impact glass and agglutinates. A dark agglutinate grain is located in the upper left, with an included colorless bubble.
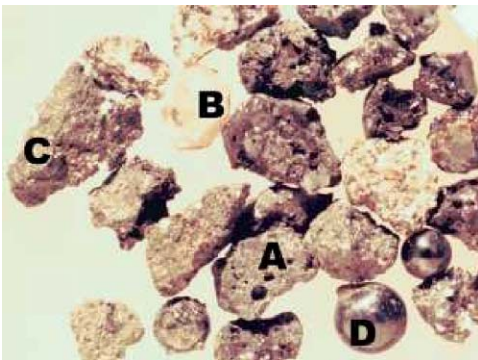
Regolith rock components NASA Photo S70-55663
Fragments of the main types of lunar rocks are found in this sample: basalt (A), anorthosite (B), and breccia (C).
The abundant glass spherules (D) are products of impact melting under meteoritic bombardment.
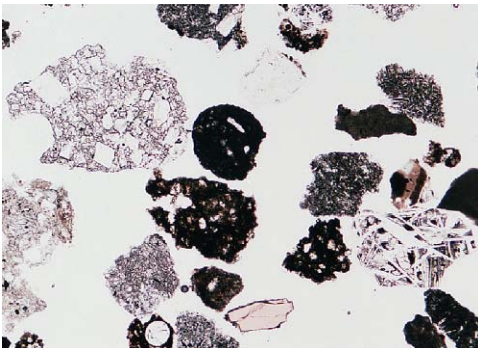
Highland Regolith 68501
Field of view 2 cm long dimension
Sample 68501 is a mature lunar highland soil from the Apollo 16 site that illustrates some of the rock types from the heavily cratered highlands. They include feldspathic crystalline rocks of anorthositic or noritic composition, but many of the particles are microbreccias. Most of the dark, porous fragments are agglutinates. The clear fragments are plagioclase. Breccias containing fragments of feldspar are also present.
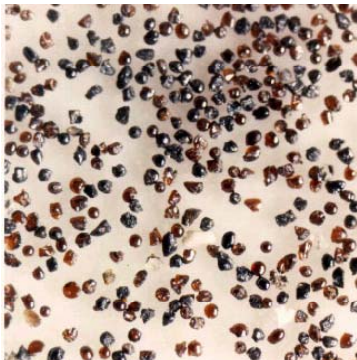
Orange Soil 74220
Sample 74220 is nearly pure orange glass (83%) from Shorty Crater, Apollo 17 at Taurus-Littrow. The average grain size of 74220 is ~40 μm (image is of a sieved fraction above 100 μm). Adjacent black glass beads only differ from being rendered opaque by devitrification. Orange soil was found to be enriched in volatile elements (Zn, Pb, S, Cl, etc.) and the glass beads have a thin coating of condensed volatiles. None of the glass in this sample is similar to lunar agglutinates, nor contains broken mineral or lithic fragments characteristic of impact glass. As such, it is distinct from other lunar soils and is described as a pyroclastic deposit.

Figure 2.4 The Nature of Lunar Materials: Lunar Regolith I

LUNAR REGOLITH
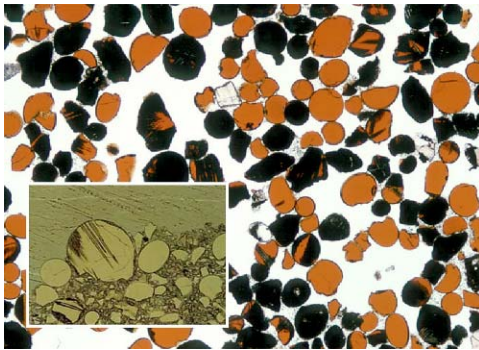
Orange Glass 74220
40X, plane polarized light. Field of view 4 mm long dimension
This sample predominantly is comprised of orange, partially devitrified (black) glass spheres, and a small admixture of mare basalt fragments. The particle size is ~20 to 45 μm. Erupted basaltic melts were fragmented at the vent and followed ballistic trajectories. Those that quenched to glass without nucleating crystals are of clear orange color, caused by high Ti content. The black ones contain olivine crystals that grew inward from the surface in blade shapes. The crystallization of many tiny ilmenite crystals on the olivine blade margins generates the black color (see insert).
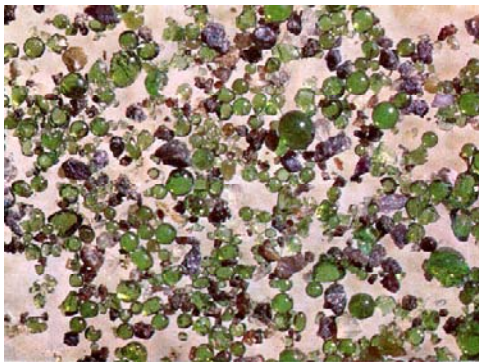
Green Glass 15421
Sample 15421 was collected in the form of friable clods several centimeters in diameter from around Spur Crater on the Apennine Front, Apollo 15. Although most lunar surface glasses are formed by meteorite impacts, these green glass beads are thought to come from the spraying of low-fluidity lava in a vacuum by fire fountains. Ranging from 40 to 250 μm in this image, these beads are sometimes found in presence of red and yellow-brown glasses. Reflecting multiple variations in composition, green glass is rich in Mg (~18% MgO) and volatile elements, and often coated with ZnS.
Credit: *Carusi et al.* (1972)
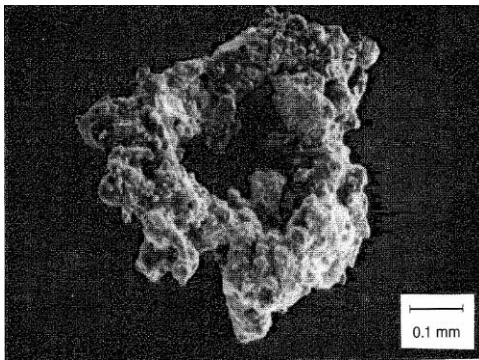
Agglutinate particle NASA Photo S87-38812
The complex shapes and surface features of these particles reveal their impact origin. Generally small (< 1 mm), Comprised of various particles (mineral grains, glasses) fused together by vesicular, flow-banded glass, they make up about 25 to 30% of the regolith and as much as 65% of some samples. Unique to the Moon, they always contain sub-micron Fe metal droplets (nanophase Fe) and solar-wind gases (He, H). The displayed agglutinate, removed from sample 10084 (Apollo 11), has a glassy surface extensively coated with small soil fragments.
Credit: *D.S. McKay et al. (1991)*
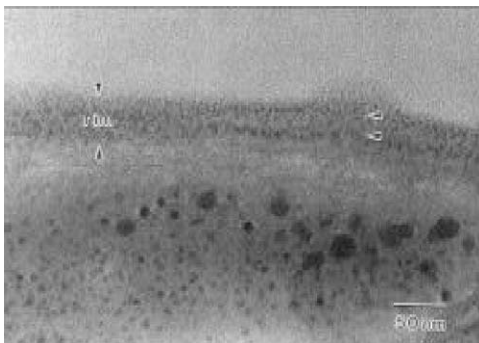
Nanophase Iron in glass
Metallic Fe in the single-domain size range (30 to 100 Å) is found in abundance in agglutinates and glass rinds of mature soil particles. The formation of these nanoparticles through reduction of available Fe-silicates is responsible for the magnetism of the smallest size fraction of the lunar regolith.
Credit: *D.S. McKay*

Credits: Images and descriptions of thin section photomicrographs by K. Hollacher, Dept. of Geology, Union College. Other images from Lunar Sample Compendium by C. Meyer, NASA JSC.

Figure 2.5 The Nature of Lunar Materials: Lunar Regolith II

2.6　　　Research and Technology Development Efforts Requiring Lunar Simulants

Lunar surface operations require the development of a suite of technologies capable of performing a wide variety of activities and functions. Some of these activities, such as landing, operating mobile surface systems, and in situ regolith characterization, are among the earliest in the chronology of missions while others like EVA or chemical extraction of elements from the regolith may only be planned for lunar sortie missions. All these technologies share a common trait: they will all come in contact with the lunar regolith. For this reason, they require the use of SLRS materials during their development and testing phase. This approach was successfully adopted during the Apollo program and yielded a suite of five NASA standard Lunar Soil Simulants (LSS1 through LSS5) used for the development of drills, tools, and LRV systems. Depending on the functions they perform, the technologies under development are affected differently by certain properties of the regolith. In turn, this translates into specific requirements on the degree of fidelity with which a simulant material must reproduce the properties of the original lunar material. The following paragraphs explicitly describe the critical properties of the regolith that affect several categories of lunar activities. This information is based on the findings of the 2005 Workshop and is to be used to establish the requirements on the simulant materials that must be provided.

2.6.1　　　Physical Regolith Processing

Development work on technologies designed to interact with the lunar regolith through mechanical actions relies on our knowledge of the behavior of granular materials in the unique lunar environment (e.g., vacuum, 1/6 g, temperature extremes between illuminated and shadowed areas, full solar spectrum, and photoelectric charging effects). State-of-the-art knowledge of granular materials behavior for terrestrial applications still lacks the foundation of other fields such as chemistry, fluid physics, and thermodynamics. This explains in part that state-of-the-art soil handling equipment used on Earth is reported to have as much as 1000 times the failure rate of other categories of industrial equipment. It cannot be overstated that our understanding of the behavior of such unique granular material as lunar regolith in its own unique lunar environment is very scarce at best. This situation was examined in further detail during the 2005 Workshop on Granular Materials in Lunar and Martian Exploration (http://weboflife.nasa.gov/regolith.htm). Our knowledge in these matters is essentially based on a few small scale core drilling and excavation tests conducted by unmanned robotic landers (Surveyor, Luna) and the time-limited experiences of twelve Apollo crewmembers who performed drilling, excavation, raking, walking, and driving on the lunar surface. While the collected data, the first-hand accounts of the crews, and the images they captured are invaluable, experts agree that we need major advances in lunar regolith rheology and associated scaling effects in order to design mission hardware with adequate safety factors.

The exploration initiative, introduced by President George H. Bush in the early 1990s, resulted in advances in regolith processing techniques. The availability of quality simulants such as JSC-1 was invaluable to that work, but continued research and development are still needed for successful lunar operations. This tremendous research and development effort will be based on the extensive use of software simulation tools used in granular materials research and also on

extensive experimental testing in simulated lunar environments using appropriate regolith simulant materials. It is important to note that providing a simulant material with the right grain properties is only the first aspect of achieving accurate simulation of the behavior of that granular material during testing. In fact, the preparation of simulant material through drying, packing or settling, and evacuation of the test atmosphere is critical to obtaining accurate data for technology development. A selection of geotechnical and engineering properties is presented in Table 2.1 for comparisons between the lunar regolith and cohesionless terrestrial soils. Such data illustrates the importance of the choice of materials in testing any hardware designed to handle or process the regolith.

The most significant properties of these simulant materials as they apply to specific research and development work are outlined in the following paragraphs.

2.6.1.1   Drilling

This activity involves the use of drilling equipment to place scientific instruments downhole, to retrieve cores of regolith for evaluation, or to prepare regolith for construction purposes. It is anticipated that the absence of water on the Moon will require further development of dry drilling technologies that were initially tested on Apollo missions.

While various drilling techniques exist or are proposed, the most widely used method employs a rotary or rotary-percussive drill bit. Already used successfully during Apollo missions, such drilling typically relies on causing the drilled material to fail when subjected to the shearing forces applied. The shear strength of the packed regolith depends on bulk properties such as grain size distribution, bulk density, cohesion, angle of friction, and particle characteristics such as grain shape and hardness. The shape of regolith grains affects their ability to interlock, increasing friction and shear strength while hardness and angularity dictate the abrasion of the drilling tool. Changing the volume fraction of glass particles of specific shapes in crushed basalt, for example, would yield a simulant of different drilling ability than plain crushed basalt.

The development of two drilling devices was accomplished for the Apollo program. One is the Apollo lunar surface drill and the other is the Apollo rock core drilling device. The development of these devices required large numbers of tests using standardized simulant materials at a time when little information was known about the lunar regolith. NASA standard simulants included *Standard Basalt*, *Standard High Density Basalt*, and *Standard 43% Vesicular Basalt* (*Crouch*, 1968). Grain hardness and apparent cohesion of the soil were found to be primary factors of influence in optimizing the drill bit design. Although the dense basalt was chosen as the benchmark for performance tests, it was noted that vesicular basalt often caused greater degradation of the drill bit.

Table 2.1 Compared Values for Selected Geotechnical and Engineering Properties of the Lunar Regolith and Cohesionless Terrestrial Soils (*Carrier*, 1971 for most lunar regolith data).

	Lunar Regolith	Terrestrial Soils (Dry, Cohesionless)
Geotechnical Index Property		
Relative Soil Density	65% in top 15 cm depth (medium to dense) 90% below 30 cm depth (very dense)	65% to 75% is practical limit for field compacted terrestrial soils
Bulk Density, ρ	1.4–2.2 g/cm^3	1.4–1.9 g/cm^3
Specific Mass of Solids, ρ_s	> 3.32 g/cm^3, Basalt particles 1 to > 3.32 g/cm^3, Agglutinate/glass 2.9 to 3.1 g/cm^3, Breccia	2.7 g/cm^3 for most terrestrial soils
Engineering Property		
Unit Weight, γ	2.9–3.6 kN/m^3 (at 1/6g)	14–19 kN/m^3 (at 1 g)
Cohesion, c	0.1 to 1 kPa	0 kPa for dune sand
Friction Angle, ϕ	30° to 50°	30° to 35° for dune sand
Ultimate Bearing Capacity, q_{ul}	25–55 kPa, intercrater areas < 25 kPa, crater rims (*Basilevski*, 1984) 6–419 kPa, calculated range for 0.1 m footing width on level ground 6000 kPa for 1 m footing width	30–60 kPa, stiff to hard clays 20–60 kPa, compact sand and gravel < 20 kPa, loose gravel and sand, 10–31 kPa, calculated for 0.1 m footing width on level ground in dune sand)
Allowable Bearing Capacity, q_{all}	8 kPa (1 cm acceptable settlement depth) 0.2 psi recommended	100–300 kPa, compact sand < 75 kPa, soft clays and silts (1 cm acceptable settlement depth) Dune buggies: 15 psi tires
Permeability, K	1–7x10^{-12} m^2 (1.65x10^{-3} cm/s)	10^{-13}–10^{-16} m^2, very fine sands 10^{-4}–10^{-7} cm/s, silts

2.6.1.2   Excavation

Excavation processes describe the removal and relocation of lunar regolith as a part of mining and construction activities and primarily involves the use of dozing and other blade-type mechanisms.

The rheological behavior (flow properties) of the regolith is a key property of the bulk material during excavation. As an example, it manifests itself in the angle of repose of a regolith slope

forming a trench or an erected berm. The regolith's rheological behavior also governs its ability to flow through hoppers and other feeding mechanisms for resource processing reactors. While scale-sensitive (it is very important for materials of small particle size ranges), this behavior is in turn dependent on bulk regolith properties such as density, angle of friction, compressive strength, and shear strength. Shear failures are common in geotechnical applications and accurate values of shear strength for soils are critical to validate engineering designs. Shear strength of soils under load is directly related to friction between grains and provides a measure of aggregate interlock and soil structure. The resulting resistance to motion under load is an important process of energy loss in excavation for which design of excavation equipment requires very reliable values. Flow characteristics also depend strongly on the cohesion of the soil, which merits particular attention when applied to lunar regolith. Lunar soil is deemed cohesionless in the traditional definition of soil cohesion, since it does not derive its cohesion from material such as clay that provides inter-particle adhesion after drying (*Craig*, 1992). In the absence of a liquid environment, lunar regolith is nevertheless a cohesive soil that derives its apparent cohesion from angular, re-entrant particles interlocking during settling. These bulk characteristics are derived from a set of specific properties at the particle/grain scale: grain size and grain size distribution, grain shapes and grain shape distribution, grain hardness, friability, and electrostatic surface charge which can be reproduced with various degrees of fidelity in a lunar simulant.

Grain size distribution affects the resistance to mechanical action as evidenced by the greater ease with which poorly graded soils excavate compared to well-graded soils. Reproduction of grain size distributions with high fidelity is crucial. However, it is important to recognize that specific landing sites may exhibit grain size variations.

Grain shape distribution affects the amount of grain interlock and resulting friction. The presence of glassy particles of various shapes in the lunar regolith is expected to vary the overall flow properties of the soils. For example, spherical particles will likely improve the flow characteristics relative to soil without glass, while angular and other irregular shaped glass particles will interlock and impede soil flow when present in large quantities. Glass particles of various shapes must be incorporated in lunar regolith simulants that are made primarily of minerals to create soils with proper apparent cohesion and rheology.

Grain hardness is a major factor in any situation where mechanical abrasion of components will occur. The simulant must be at least in the same class of materials as the lunar soil with respect to hardness (primarily it should not be any weaker than lunar soil). At small particle sizes, hardness has an indirect impact on flow characteristics. Small, hard particles such as sand are generally easy to excavate. However, soft particles can also be easy to excavate depending on other properties.

Friability of a portion of the lunar regolith comes from particles with unique characteristics that are the result of the mechanisms of formation of these particles in the lunar environment (see Section 3.0, Lunar Science). Of particular interest for the reproduction of geotechnical properties, highly porous, sponge-like particles and glassy agglutinates are present in large volume fractions in the regolith and their friability (low fracture strength) is thought to affect the bulk behavior of the regolith when subjected to equipment forces.

Electrostatic charges distributed on the grains will affect physical/mechanical behavior by changing the regolith cohesion, and will influence the accumulation of dust on excavating equipment. Activities such as excavation also generate large amounts of dust from regolith fines (at surface cuts) and this ultrafine fraction will need to be simulated to examine its interaction with excavating equipment. Requirements for dust simulants are described further in Section 2.6.5, Dust Mitigation Technologies.

It must be noted that drilling or excavating at greater depths may reach the underlying material which is referred to as *megaregolith,* and which may behave more like rock than unbonded regolith (Lunar Sourcebook, pp. 93, 286). Properties such as tensile strength of such material will dictate its fracturing behavior but such data is not available at this time.

2.6.1.3 Regolith Handling and Transport

Handling and transportation activities pertain to the movement of regolith from one location to another on the lunar surface and potentially in lunar caves. These activities are primarily centered on the transportation of lunar regolith for the purposes of processing. They take place after the extraction of the regolith from its original location and deal with the movement of the material using various pieces of equipment including loading bins, conveyor belts, chutes, hoppers, feed screws, etc. Given the state of our knowledge in granular materials behavior, the handling and transportation of large amounts of regolith on the Moon presents significant risks of failure for equipment and safety risks for the crew involved in these operations. Certain issues deal with the interaction of the regolith and mobility traction systems used in transport; these are addressed in Section 2.6.2, Lunar Mobility Systems.

The notion of scale is paramount in this area. The soil mechanics and flow properties of a boulder field are vastly different than that of a pile of sub millimeter-size grains. **Grain size distribution** and **grain shapes** of the regolith impact the ability of particles to interlock and also impact the overall flow properties in hoppers and chutes under partial gravity. They also define the angle of internal friction and the angle of repose of packed and loose regolith that are critical values to determine material quantities, cross sections, and geometric designs for above-ground fills, roads, berms, and slopes. The presence of a large fraction of sub-100 μm particles in the lunar regolith with both strong **magnetism** and **electrostatic surface charges** presents a great challenge for the design of transport equipment through which large amounts of material would flow. Such parameters and **grain density** will also impact the soil's apparent cohesion after excavation and the behavior of piles and slopes during transport under low confining stresses of partial gravity. **Grain hardness** linked to **grain mineralogy** will determine the abrasion suffered by all equipment.

2.6.1.4 Crushing

Crushing activities involve the reduction of the size of rock and soil from boulder to dust sized material in support of activities such as construction and resource extraction. While most activities may not require crushing of the subsurface lunar regolith, activities such as feeding regolith to chemical processors, often require crushing of the material to loosen the particles or break packed aggregates. If deep materials such as megaregolith are brought to the surface, or if rocks are part of the excavated material, crushing becomes a necessary task.

The capacity of rock material to fracture is highly scale-dependent, so it is critical to define the physical scale for which fracture properties are required. Scale is found in the dimensions and aspect ratios of the material and also in the spatial variability of the material properties. The scale of the surface and subsurface regolith is limited to rocks of a few centimeters in dimensions. Simulants for such materials will have to reproduce their compressive strength that defines the resistance to crushing and the tensile strength of elongated particles or rocks.

It is important to note that lunar soils exist in a hard vacuum and are charged by the photoelectric process. The crushing of such material will likely create suspensions of charged dust that will interact with any equipment surfaces and mechanisms.

2.6.1.5 Beneficiation

Beneficiation processes take an unsorted and unclassified raw material and produce a product that is sorted on one or more properties, such as size or modal mineralogy, as input for subsequent processes. They may be employed in the preparation of soils for construction or to separate target minerals for resource processing. Examples of beneficiation include segregation of size fractions through sieving by using lunar gravity, centrifugal forces, or segregation of specific components of the regolith (e.g., minerals and dust grains) by magnetic or electrostatic separation. Simulants used in beneficiation development work must reproduce accurately the specific properties of the lunar regolith that constitute the basis for a given beneficiation technique. These include grain size distribution and grain shapes, surface charge of the particles, magnetism of the grains, and grain mineralogy. All properties may not need to be duplicated in a simulant but special attention must be paid to the interrelationships between some properties. For example, the magnetic properties of lunar regolith depend on the grain size where strong magnetism exists for virtually all dust grains below 10 μm that contain nanophase iron, while the magnetism of larger grains depend on the presence of certain minerals. The electrostatic properties of the particles exhibit the same relationship with grain size and are also likely to play a role in any effort of beneficiation by either promoting the formation of particle aggregates or increasing the adhesion of particles to the machinery.

2.6.2   Lunar Mobility Systems

The movement of vehicles on the Moon will require an increased understanding of the behavior of lunar materials under load conditions and the effect of lunar dust in terms of abrasive and contamination issues. The remarkable successes of rovers on the martian surface have yielded a wealth of knowledge about the challenges faced by planetary rovers. The drastic differences between the lunar and martian environments and their respective regoliths require that specific solutions be found for roving vehicles on the moon. Fortunately, future advances in lunar mobility technologies will benefit from the extensive work and experiences from the Apollo LRV program and to some extent, the Soviet Lunokhod program if documentation is still available.

The lunar regolith affects different systems on a mobile vehicle. It interacts primarily with the traction system, which can be wheels, tracks, or the pads of a walking device. It also comes in contact with joints, bearings and various parts if projected by the traction system. The dust fraction of the regolith is of particular concern since Apollo missions showed that it accumulates easily on a variety of surfaces (i.e., radiators, fenders, etc.), affecting their nominal performance. The development of vehicle traction designs rely heavily on accurate simulation of the geotechnical properties of the soils that will be encountered is evident in the LRV reports, (*Green*, 1971). Knowledge of the bulk density, apparent cohesion, angle of internal friction, and shear strength of the prepared test beds must be obtained. In addition, the dynamical nature of the interaction between regolith and traction systems requires a thorough understanding of the rheology of the regolith over a wide range of mobility speeds and surface loads. In fact, the amount of wheel slippage and the amount of regolith retained in the open mesh wheels of the LRV was dictated by the rheological behavior of the regolith in these conditions and these test results were markedly different when sand was used as a simulant instead of Lunar Soil Simulant (LSS) crushed basalt.

Simulations of both the geotechnical and rheological properties of the lunar regolith in experimental tests thus require the proper choice of simulant material and proper preparation of the test beds. The chosen simulants must first reproduce the following grain properties: overall grain size and grain size distribution, grain shapes and distribution, hardness (abrasiveness), and mineralogy. Preparation of these simulant materials in test beds should aim at reproducing the range of bulk density, cohesive, and frictional properties known for the lunar regolith. The durability of simulant materials also must be taken into account when multiple test cycles are performed, thus causing repeated crushing of the materials. The grain size and shape distribution of such simulant materials would change over the course of multiple tests. Tests conducted on simulants of regolith with high fractions of crushable materials (e.g., agglutinates and vesicular grains) and loose colluvial regolith, such as material found at bottom of slopes, are of interest to evaluate the deformation of the lunar regolith when subjected to repeated vehicle traffic.

Other regolith properties deemed important for the development of lunar mobility systems include electrostatic surface charges and magnetism of the grains which are likely to affect the accumulation of particles on various surfaces and their adhesion over time.

The development of the LRV wheel design was performed using four standard lunar soil simulants labeled LSS1 through LSS4. These materials were based on the same starting soil prepared in four different manners to obtain geotechnical characteristics similar to what had been identified in Apollo 11 and 12 regoliths. Apollo 14 mission data led to the addition of LSS5 to reflect higher shear strengths that were encountered. The granular soil was crushed basalt with angular and sub-angular grains, reported to exhibit "a small amount of cohesion when moist and/or compacted." The preparation of these materials for tests included plowing and air drying, compacting by vibrational compaction, and wetting with water. In addition, fine dune sand was characterized and used in comparative tests.

2.6.3   Resource Processing (Extraction, Transformation)

Rocks and regolith constitute the major lunar resource that a lunar outpost may exploit to achieve some degree of self-reliance and ensure its long-term survival. The chemical composition of rocks and regolith allow for the extraction of oxygen for life support and of silicon and metals for solar-cell fabrication and parts manufacturing. The transformation of the glass-rich regolith can lead to the fabrication of glass and glass-ceramic parts for a variety of purposes. The presence of volatile species of solar-wind origin captured in the subsurface of regolith grains offer the potential for extraction of valuable chemicals such as hydrogen, helium, and nitrogen. The yet-to-be confirmed presence of water ice at the lunar poles could offer a resource of extremely high value for long-term lunar operations. Extraction and transformation processes encompass both physical and chemical treatment of the regolith and rocks during which they may be crushed, ground, melted, vaporized, sublimated, sintered, reduced, or oxidized to deliver products used in life support, propulsion, structural construction, radiation shielding, or energy production.

Among all the possible activities to be conducted on the lunar surface, the extraction and transformation of resources from the regolith will be most dependent on its properties. As such, the development of these technologies for lunar operations requires the use of simulant standards which reproduce the largest number of regolith properties to make possible performance comparisons between techniques and qualification of hardware for flight.

While the processes and technologies being considered for transforming and extracting from regoliths vary widely in their operating conditions, one is able to identify the properties of the regolith that play important roles and that must be found in the simulant materials. **Grain size and distribution** defines surface area and reactivity in chemical processes, impacts the ability to sinter regolith into ceramic materials or concrete, and also defines the bulk density which impacts the heat capacity of the regolith mass when thermally processed. **Grain shape** affects sintering kinetics and structure of final sintered products. It also impacts the intergranular porosity of the regolith, which influences the ability to extract water ice from the pores. **Intragranular porosity** and vesicularity impact the efficiency of gas and liquid-based processes, and impact strength of concrete materials by providing failure points under pressure. **Chemical composition** defines the concentrations of specific elements of interest (e.g., oxygen, hydrogen, metals, silicon) for extraction as well as oxide composition and potential contaminants for glass and ceramic formation. The concentration of certain chemical species varies as a function of grain size (e.g., solar-wind volatiles) or mineralogy (e.g., ilmenite). These variations affect

process efficiencies and are important to simulate for process and technology development when these resources are targeted. **Mineralogical composition** varies with location and affects the properties of the regolith during processing (e.g., grain hardness, ability to retain volatile species, oxygen fugacity, and thermal properties such as melting points and melt viscosity). The **magnetic and electrical properties** of lunar regolith components are critical in processes using electrolytic reduction or microwave and radio frequency (RF) heating. Such properties depend on the mineralogy of the grains and the presence of nanophase elemental iron embedded in glass rinds. The **electrostatic charge** of the grains may play an important role in the separation of fines and larger grain sizes, while clustering and adhesion of charged particles to surfaces affects the continuous handling operations and the design of fluidized bed reactors. The presence of these charges can also interfere with microwave, RF, and electrolytic processing.

2.6.4 Radiation Shielding

The lunar surface presents significant radiation shielding challenges due to exposure risk for humans and equipment from Solar Energetic Particles (SEP) and galactic cosmic rays. The exposure to SEP during a three to four hour event on one of the lunar missions reached a dosage of two or three rems per hour. SEP events are difficult to predict, and a safe haven would be necessary with the capability for occupation for several days during a radiation event. Shielding from micrometeorite impacts is also necessary as the absence of a lunar atmosphere allows incoming meteorites to impact the surface unabated. Galactic cosmic rays are in continuous flux and vary with the solar cycle, and SEPs are sporadic, lasting hours or days. Two types of radiation shielding are required; low atomic number materials having a high cross-section for the energetic heavy particles that are present in galactic cosmic rays, and high atomic number materials to absorb γ-rays and energetic radiation. Shielding must be able to limit the generation of neutrons that are produced by incoming energetic particles. Excellent shielding materials include hydrogen (as hydrocarbons), oxygen, and water. Calculations show that a meter or two of water is sufficient for shielding purposes. The use of water shielding in habitat design is attractive although issues of complexity and reliability arise, as water usage for human consumption would require its immediate replacement and accidental losses of water would leave the crew at risk.

The use of lunar regolith as radiation and impact shielding material is also under serious consideration since it is readily available in situ without the high production or importation costs associated with the other candidate materials. Previous studies have shown that regolith overburden blankets on the order of meters in thickness are required for shielding and the requirements for micrometeorite protection are for thicknesses on the order of several centimeters. These thicknesses place constraints on human habitation and activity, and also have impact on design parameters for transportation vehicles.

Radiation shielding requirements on simulant materials focus on the accurate reproduction of regolith elemental composition. **Chemical composition** is critical to establish the stopping power of the fabricated shield and determine the optimum thickness to achieve. **Particle density** and **bulk density** of piled regolith are also critical parameters to reproduce to establish the areal density of constructed shields. Additional requirements are identical to the ones already

mentioned in the case of building shields by excavation of the regolith and transforming the regolith into sintered materials (i.e., concrete and glass ceramics).

2.6.5   Dust Mitigation Technologies

The pervasive distribution of lunar dust and the anecdotal experiences of the Apollo astronauts have demonstrated the great importance of dust mitigation in planning for lunar missions (*Gaier*, 2005). Dust problems fall into two categories, astronaut toxicological issues and material abrasion and contamination issues. Experience in the Apollo missions included aspects of both problems. The lunar EVA suits exhibited increases in gas leak rates after each sortie due to dust invasion, deterioration of mobility, obvious scratching and damage to the articulating joints of the suit, and abrasion damage to the visor that affected visibility. Persistent accumulation of dust on thermal radiators on the LRV prompted crews to spend time brushing it off, which proved largely ineffective. Lunar dust caused irritation for the astronauts when it was inhaled and entered the mucous areas of the mouth and eyes. The dust was found in the astronaut EVA suits, the Lunar Excursion Module (LEM), and even contaminated the Apollo command module. These facts illustrate the magnitude of the lunar dust problem and the high priority that must be placed on dust mitigation.

The specific need for a lunar dust simulant was deemed of high importance during the planning phase of the 2005 Workshop, and was given equal importance with topics of physical and chemical nature. Technical and planning discussions started during the 2005 Workshop and have continued to emphasize dust issues and the need to implement an SLRS material that is made up entirely of the dust component.

The lessons from Apollo development work in the use of standard simulant materials are useful once again. Although much less was known of the lunar dust prior to the manned missions, extensive testing of dust degradation of surfaces and removal methods was done using LSS4 crushed basalt as a standard simulant material sieved to sizes below 37 μm (*Mullis*, 1971). It is instructive to note that the absence of reliable data on lunar dust sizes and compositions at the time resulted in approximations for testing purposes, which on one hand yielded flight hardware that was successful in lunar operations but on the other hand was unable to design adequate dust mitigation technologies. A quote from a 1967 report (*Tatom*, 1967) states the extent of the problem at hand, "It was found that the dust problem was as critical as the most pessimistic had predicted… As a result of these tests, it was decided to conduct a test program to study the influence of vacuum on the behavior of dust as well as that of gravity."

In spite of our limited knowledge of the properties exhibited by dust grains in the lunar environment, critical properties have been identified for reproduction in lunar dust simulants. **Grain size** is the most obvious property that must be matched, although the upper size limit that characterizes the lunar dust is somewhat a matter of choice depending on the type of testing to be performed. An upper limit of 50 μm can be established based on test findings showing that larger particles are easily removed from surfaces by tapping or low velocity gas jets. Submicron particles are known to exist in lunar dust samples and further characterization of such samples is being conducted at this time. Reproduction of the dust grain size is critical for any study or testing since it affects system components in different ways. For example, submicron and

micron-size particles are very invasive for seals, joints, and fabrics, and can remain airborne in a habitat while larger particles capable of adhering to and accumulating on surfaces are of primary importance for their abrasive, optical, and thermal properties. (*Tatum*, 1967). The combination of physical, chemical, and mineralogical characteristics of lunar dust is a signature of its uniqueness as a material. The perpetual bombardment of the lunar surface by micrometeorites is the destructive process that creates the dust fraction, which consists mainly of angular glass fragments, mineral fragments, and occasionally glass microspherules of pyroclastic origin. These **angular shapes** and their **mineralogy** determine such properties as **grain hardness** (abrasiveness), chemical reactivity (i.e., toxicity and surface reactions), optical properties (solar reflectance varies with mineralogy), **magnetic properties** (ferromagnetic or nonmagnetic minerals), and **electrostatic charge distribution**. The lunar regolith is charged and the dust grains are levitated by electric fields that are established by the charge. This mechanism is thought to enable the transport of dust over some distance, but the effect has not been observed in situ. Also, the dust grains and the surfaces may be charged differentially, and by means of these attractive charges, they acquire adhesive properties. The discharge of these electrical charges on spacecraft systems is of great concern as well, given the dielectric nature of the lunar surface. In the absence of a lunar magnetic field, magnetic dust particles (either containing ferromagnetic minerals or nanophase elemental iron) will be attracted to any object that has its own magnetic or electromagnetic field. Such facts pose significant challenges in the design of mitigation technologies effective enough to ensure nominal operations for long-duration and repeated activities on the lunar surface.

Challenges remain in the study of electrostatic charging and surface bonding in the high vacuum environment. For these reasons, such characteristics should be attributed to the lunar dust simulants through preparation in vacuum chambers rather than being part of the material during its production.

2.6.5.1 Toxicity of Lunar Dust

Toxicological data on lunar dust in humans does not exist beyond the anecdotal reports of those Apollo astronauts who reported discomfort due to inhalation and eye irritation. While no ill effects resulted from these brief incidents, this demonstrated that airborne lunar dust can be easily breathed or ingested by humans in lunar gravity (*Darquenne et al.*, 1997). This safety risk requires the design of preventative methods and operating procedures for long-duration lunar stays and repeated EVAs. The level of risk abatement necessary depends on our knowledge of human toxicological effects of dust particles. The issue was recently examined at the Workshop on Biological Effects of Lunar Dust held by NASA Ames Research Center in March, 2005 (http://lstworkshop.arc.nasa.gov). Toxicological studies recommended by the expert panel will follow standard protocols adopted in medical research and will rely on both a certain amount of lunar dust samples and a larger amount of lunar dust simulants. Our knowledge of lunar dust properties and the known toxicology of similar terrestrial materials will enable the generation of materials requirements for dust simulants.

Particle size is critical with respect to effects on biological systems and is a known, major factor in human health. This includes inhalation, ingestion, respiration, and contact with the skin and eyes. This is of major importance for the very fine-grained fraction. A large body of medical

information gathered over the past two centuries shows that grain size is a major determinant in the pathogenicity of mineral dust. Silicosis is caused by inhalation of fine silica particles of which the smallest (< 10 μm) find their way into the lung alveoli. Lunar dust is also known to contain nanoparticles (< 100 nm), which may present a toxicity risk analogous to documented cases of surface-active TiO_2 nanoparticles. Because small differences in grain size can have a major effect on disease development (e.g., asbestosis), a high-fidelity simulant will be needed, but toxicologic validation with existing lunar dust samples will also be required. **Size distribution** will determine the amount of interaction with different systems and parts of systems in the body. This is particularly true for the lungs but can pertain to other systems as well. The distribution of grain size will impact the ability to produce high-fidelity dusts for toxicologic testing, because a mixture of finest fraction with larger particles determines the final shape and composition of the agglutinate portion of actual lunar dusts. Because of their unusual morphologies and other mineralogic qualities, these agglutinates may have specific pathogenic potential not replicated in terrestrial mineral dusts.

Grain shape is important when particles interact with the respiratory system. Asbestos is known to cause disease because of its aspect ratio. Other factors include surface area and aspect ratio. Grain roundness may also be important as in silicosis. Grain shape is known to be a very important factor in the pathogenicity of mineral dusts on Earth, since in addition to grain size, it determines whether the cellular clearance mechanisms in the lung (e.g., macrophage phagocytosis) could be inhibited. The fidelity of this shape should be high, since the difference, between fibers and spherical particles is known to be important in terrestrial human disease (e.g., asbestosis). **Particle density** affects the ability to aerosolize the particle and dictates its flight both in free space and through the respiratory passages. This behavior is critically affected by reduced gravity (*Darquenne et al.*, 1997). Next to particle size, the biochemical reactivity of **mineral** dusts is a critical factor that can make the difference between rejection of the particle from the body and the development of a deadly disease. Interaction of minerals with the body depends on reactivity with fluids in the body; asbestos and silica are harmful, in part, because they are bio-durable while Pb-rich carbonates and sulfates are harmful because they are bio-available. Tests need to be done to determine these parameters for the minerals expected in the lunar environment. Major changes in **mineralogy** due to regional variations on the lunar surface must therefore be simulated, as this would affect biochemical properties as well. The reactivity of iron in the body is under investigation as a potential factor in the development of asbestos disease due to the generation of free radicals. The documented concentrations of metallic Fe nanoparticles in the glass rinds of lunar grains (*Keller*, 1997) must be kept in mind if toxicity of silicates can be tied to Fe nanoparticles (which do not exist in terrestrial natural dusts), and may require their inclusion into lunar dust simulants at a later date. It is conceivable that the dust particles carried by astronauts would remain electrically charged in the dry air of a lunar habitat. The possible effects of electrostatically-induced charges on the toxicity of particles are still a matter of conjecture and will have to be determined.

2.6.6   In Situ Regolith Evaluation

Apollo surface experiments on the Moon included measurements and sampling of the lunar regolith. It is important to include in situ test measurements as the behavior of the regolith, due to compaction, drives the material properties that must be specifically addressed for lunar

exploration. The in situ measurements from the Apollo missions thus form a foundation for future missions based on this set of engineering data. Upcoming missions will have the need for near real-time evaluation of regolith materials. It is anticipated that selection of regolith components of the appropriate size and composition by a rover will require real-time identification and selection of material. Processing of this material will also require real-time monitoring of the streaming processed material and inspection of the input and output portions of the process. It is unlikely that any ongoing process will be able to depend on an operator on Earth for detailed instructions during these operations. This emphasizes the need for autonomous operation and implicitly requires in situ evaluation of materials during a host of activities on the Moon.

The development of technologies for in situ evaluation of geotechnical characteristics of the lunar regolith and rocks requires simulants with similar requirements to the ones described in Section 2.6.1, Physical Regolith Processing. Technologies in use or under development for the Mars exploration program for the in situ evaluation of chemical and mineralogical compositions in martian rocks and dust also make use of geological simulants of terrestrial origins during development and testing phases. These techniques include proton X-ray spectrometry, neutron spectrometry, Mössbauer spectrometry (*Morris et al*, 1992 and *Morris et al*, 1997), Raman spectrometry, and optical and electron microscopy techniques, and will find applications on instrument platforms for lunar missions. However, the specificity of the lunar regolith places additional requirements on such simulant materials in order to qualify evaluative technologies for lunar operations. These include the reproduction of the following characteristics: distributions of **nanophase iron** in dust particles, mixture ratios of **glass** material with **minerals**, angular **grain shapes** with similar **optical properties**, **magnetism**, and **electrical surface charges**. These properties are deemed important both to validate the methods chosen to characterize the lunar regolith in situ as well as to reflect the operational challenges expected during these assessments.

2.7 Ranking of Lunar Regolith Properties by Workshop Attendees

From the previous discussions of lunar regolith properties, it is apparent that the regolith has a long list of physical, chemical, and mineralogical properties that define the behavior of the soil and can be used to delineate properties that are central to simulant development. During the 2005 Workshop, attendees ranked the regolith properties in terms of the dominant material properties that are expected to be critical for activities conducted on the lunar surface, as well as for the development of SLRS materials. The properties ranking is organized in Table 2.2 by material category (i.e., geomechanical, physical, grain-specific, chemical, mineralogical, and multi-category). Within each category, the properties are grouped and highlighted if they were ranked in the top 10 list. This organization serves to group properties by their common category.

It should be emphasized that Table 2.2 contains only those material properties of the lunar regolith that must be possessed by SLRS materials as determined by expert consensus at the 2005 Workshop. According to this consensus, these properties must be duplicated with medium or high fidelity.

The ranking lists both physical and chemical properties. The dominant regolith properties are, in decreasing order of ranked importance, grain size, grain size distribution, particle density, glass

composition, bulk density, modal mineral composition as a function of grain size category, grain shape, bulk chemistry, magnetic properties, mechanical strength, and total modal mineralogical composition. The workshop attendees used this list to produce simulant requirements, and this requirements list will form the basis for specific simulant development guidelines.

This ranked list allows several basic interpretations to be made. First, it is possible to satisfy a number of regolith properties by careful selection of the simulant in terms of chemistry and mineralogy. For example, a mare basalt simulant that closely matches a given Apollo mare sample has a match for bulk chemistry and mineralogy, and by definition also satisfies density constraints due to the composition. In simple terms, it is possible to satisfy this ranked list by careful selection of a simulant using compositional properties, and to mill and sieve the material in order to satisfy the grain size properties. Secondly, lower ranked properties that cannot be addressed by selection of a simulant based on composition and simple physical processing may be produced by subsequent processing operations. The basic simulant material which satisfies the most important properties is an example of a root simulant, and the modified simulant that is further processed is an example of a derivative simulant. These topics are discussed further in Section 5.0, Recommendation 1: Standard Lunar Regolith Simulant Materials.

The ranking of properties bears additional discussion based on subsequent developments since the workshop was held in January 2005. At the time of the workshop, the knowledge base of the community concerning lunar regolith simulant development was less complete than at the present. The ranking of material properties addressed lunar activities which range from physical (i.e., excavation and drilling) to chemical (i.e., element extraction and oxygen production) and the ranking of properties reflected the familiarity of attendees with the details of these activities. The ranking required an assessment of properties that required either medium or high degree of fidelity in simulants compared to the lunar regolith. These ranked properties are intended to be used for the development of root simulants rather than derivative simulants, and for this reason the importance of agglutinates and nanophase Fe appears low in the list when it is clear that these are critically important properties for evaluation of derivative simulants that have high fidelity compared to the lunar regolith.

Properties that are grain-specific rather than referring to bulk properties have also been ranked higher since bulk properties such as shear strength depend on the degree of assembly of soil particles in addition to the nature of the simulant material. These facts should be considered in the interpretation of data in Table 2.2. The development of root SLRS materials requires appropriate geological source materials and processing in order to produce a simulant that has good fidelity, and subsequent processing should be performed in order to produce a derivative simulant of higher fidelity. The relationship between activities conducted on a planetary surface and the material properties that critically affect these activities are to be coupled with the selection and development of root and derivative simulants. The subdivision of physical versus chemical activities is an arbitrary imposed boundary that requires ranking of properties in order to emphasize the importance of, for example, mineral hardness, which is less specific to composition compared to mineral chemistry, which is specific to a particular extraction process.

Table 2.2. Categorized Lunar Regolith Properties from 2005 Workshop Consensus Evaluation

Category	Category Properties Listing	
Category	**Regolith Property**	**Rank**
Geomechanical (i.e., Mechanical Strength Properties) Total Number of Ranked Properties — 11 Number of Properties in Top Ten — 1	**Compressive Strength**	**10**
	Coefficient of Friction	12
	Shear Strength	18
	Fatigue	19
	Hardness	23
	Rheology	24
	Angle of Repose	25
	Tensile Strength	27
	Fracture Behavior	28
	Impact Resistance	32
Physical Total Number of Ranked Properties — 7 Number of Properties in Top Ten — 2	**Particle Density**	**3**
	Bulk Density	**5**
	Porosity	13
	Thermal Properties	20
	Surface Area	21
	Friability	22
	Permeability	26
Grain Specific Total Number of Ranked Properties — 6 Number of Properties in Top Ten — 4	**Grain Size**	**1**
	Grain Size Distribution	**2**
	Grain Shape	**7**
	Magnetic Grain Properties	**9**
	Grain Shape Distribution	16
	Electrostatic Charging	17
Chemical Total Number of Ranked Properties — 6 Number of Properties in Top Ten — 4	**Glass Composition**	**4**
	Bulk Chemistry	**8**
	Reactivity as Volatile/Soluble Minerals	14
	Surface Reactivity (including damage)	29
Mineralogical Total Number of Ranked Properties — 4 Number of Properties in Top Ten — 2	**Mineralogical Composition as Function of Grain Size**	**6**
	Modal Mineralogical Composition	11
	Soil Texture	30
Multi-Category Total Number of Ranked Properties — 2 Number of Properties in Top Ten — 0	Implanted Solar Particles	15
	Agglutinates with Nanophase Fe	31

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3.0   LUNAR SCIENCE

Our knowledge base concerning the diversity of rock types on the Moon is derived primarily from the samples returned by the Apollo and Luna missions, coupled with remote sensing information from a variety of sources (see Figure 3.1). The emphasis on lunar science has historically been on geological interpretation in order to understand the evolution of the Moon and how it compares and contrasts with the evolution of the Earth. This material is extensively covered in the Lunar Sourcebook, and is briefly summarized here. The importance of lunar geology and mineralogy on the development of lunar simulants is also discussed.

Lunar rocks are discussed in terms of their primary mode of origin and geological setting (such as by eruption from a volcanic vent and extrusion as a lava flow to form a mare) and by their composition in terms of both bulk chemistry and specific mineral composition (such as basaltic composition and containing the minerals olivine, pyroxene, and plagioclase). The textural details of subsequent processes are used to describe the rock as, for example, a "pristine crystalline highland rock" compared to a "highly modified polymict breccia" or an "impact melt glass" (Figures 2.1 to 2.5). These descriptions thus include classification as well as genetic information for the purposes of geological interpretation.
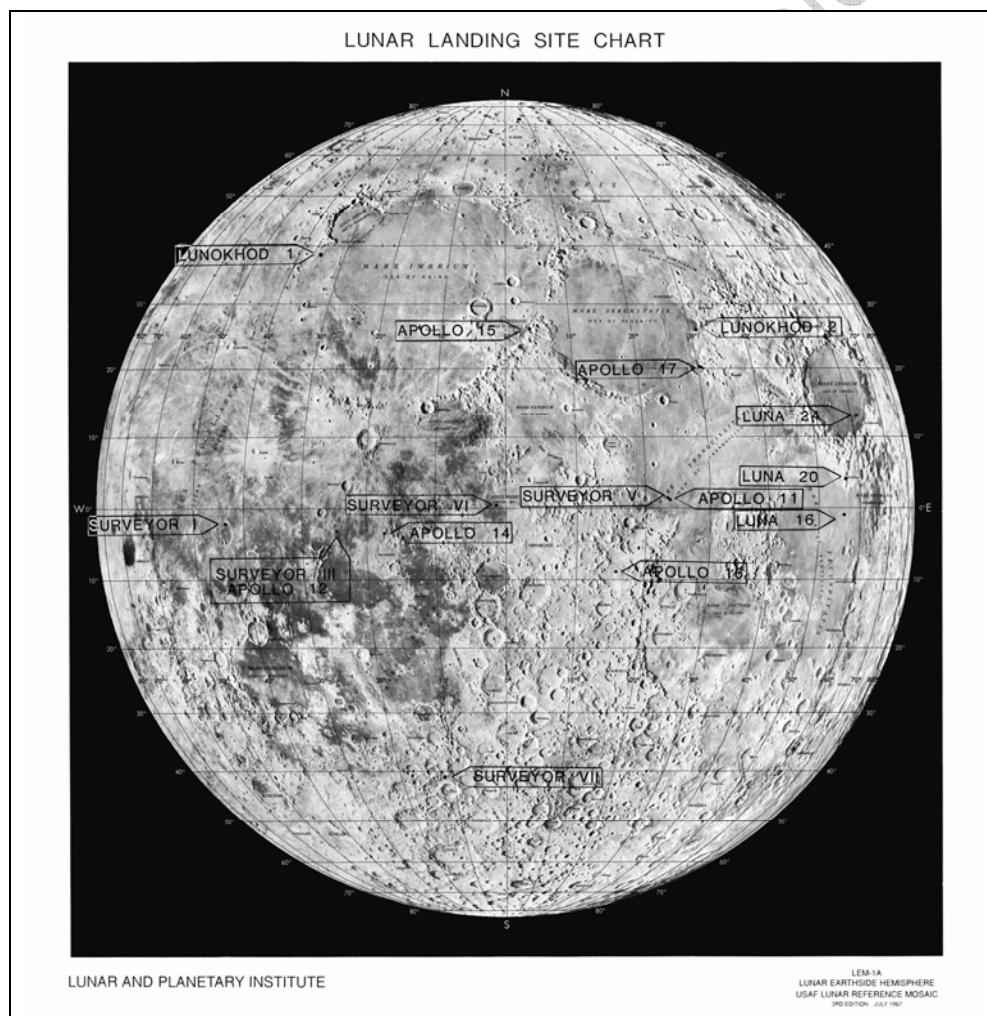
Figure 3.1 Lunar Landing Site Chart

Nearside of the Moon with locations of Apollo, Surveyor, and Luna mission landing sites. Note the use of mare rather than highland sites for mission landing locations, and the absence of sites in the vicinity of the lunar south pole.

3.1 Lunar Mare Rock Types

Two types of volcanic rocks that erupted at the lunar surface produced lava flows and pyroclastic deposits. The lava flows are similar to terrestrial flood basalt lava flows but differ in composition. The pyroclastic deposits on the Moon include Ti-rich orange glass from the Apollo 17 landing site, and green glass from the Apollo 15 landing site (see Figures 2.4 and 2.5). Orbital photographs show dark mantle deposits which may be of pyroclastic origin and may represent material such as these orange and green glasses that could be exploited as a potential ore for lunar processing operations.

The dominant mare rock type is basaltic. Lunar basalt chemistry identified from the Apollo samples is delineated based on the concentration of TiO_2, namely, *high-Ti* ($TiO_2 > 9$ wt%), *low-Ti* (1.5 to 9 wt% TiO_2), and *very-low-Ti* (< 1.5 wt% TiO_2). These chemical variations reflect the modal content of ilmenite ($FeTiO_3$) in lunar rocks, and remote sensing data indicate that lunar rocks exhibit continuous variations in ilmenite and the dependent Ti chemistry. Other chemical factors have been used to describe lunar rocks and include *aluminous low-Ti* mare basalts. The Apollo 11 high-Ti mare basalts have been further classified based on potassium content as *high-K* (> 0.3 wt% K_2O), and *low-K* (< 0.1 wt% K_2O). Aluminous mare basalts from the Apollo 14 site have very high K_2O content, averaging 0.9 wt% and have been designated *very-high-K* mare basalts. Representative major element chemistry of the mare basalts is listed in Table 3.1 and modal analyses are listed in Table 3.2. Photomicrographs of representative lunar basalts are shown in Figures 2.1 and 2.2. Mare basalts contain the minerals pyroxene, plagioclase, olivine, and ilmenite, in proportions that reflect this variation in bulk chemistry. High-Ti basalts contain large modal proportions of ilmenite, and olivine basalts contain significant olivine in the mode.

From the perspective of lunar mare simulant development, both the bulk chemistry and mineralogy of mare basalts are important. Lunar regolith chemistry and mineralogy are dependent on the proportions drawn from mare and highland source materials, so it is important to evaluate terrestrial geological materials for use as simulants in terms of these source materials. The primary variation in chemistry and mineralogy of mare basalts is due to Ti content as seen in the ilmenite mode of the rock. However, the modal variation in olivine, plagioclase, and pyroxene are also important as illustrated by the variation in bulk chemistry and mineralogy from the Apollo sample sites. From inspection of these data, it is evident that a likely candidate for a root mare basalt simulant is similar in chemistry and mineralogy to an Apollo 15 basalt which possesses a low-Ti content. The variation in Ti content can be approximated by addition of ilmenite to a base mare basalt chemistry such as the Apollo 15 composition. The root simulant concept is discussed further in Section 5.0, Recommendation 1: Standard Lunar Regolith Simulant Materials.

Glassy material is present both as droplets and fragments in lunar rocks. Lunar pyroclastic rocks are thought to have been formed by fire fountain activity which formed glassy material. Impact processes have also contributed to the development of glass in lunar soils. Apollo 11 green glass and Apollo 17 orange glass have compositional ranges that exceed those of lunar soils and may represent materials that could be exploited like ore deposits on Earth (some glasses are higher in Mg and Ti, for example).

Table 3.1 Major Element Chemistry of Mare Basalts

Oxide	Green Glass Apollo 15	Olivine Basalt Apollo 12	Olivine Basalt Apollo 15	Quartz Basalt Apollo 15	Quartz Basalt Apollo 12	High-K Basalt Apollo 11	Low-K Basalt Apollo 11	High-Ti Basalt Apollo 17	Aluminous Maria Basalt Apollo 12	Aluminous Maria Basalt Luna 16
SiO_2	45.6	45.0	44.2	48.8	46.1	40.5	40.5	37.6	46.6	45.5
TiO_2	0.29	2.90	2.26	1.46	3.35	11.8	10.5	12.1	3.31	4.1
Al_2O_3	7.64	8.59	8.48	9.30	9.95	8.7	10.4	8.74	12.5	13.9
FeO	19.7	21.0	22.5	18.6	20.7	19.0	18.5	21.5	18.0	17.8
MgO	16.6	11.6	11.2	9.46	8.1	7.6	7.0	8.21	6.71	5.95
CaO	8.72	9.42	9.45	10.8	10.9	10.2	11.6	10.3	11.82	12.0
Na_2O	0.12	0.23	0.24	0.26	0.26	0.50	0.41	0.39	0.66	0.63
K_2O	0.02	0.064	0.03	0.03	0.071	0.29	0.096	0.08	0.07	0.21
MnO	0.21	0.28	0.29	0.27	0.28	0.25	0.28	0.22	0.27	0.26
Cr_2O_3	0.41	0.55	0.70	0.66	0.46	0.37	0.25	0.42	0.37	—
P_2O_5	—	0.07	0.06	0.03	0.08	0.18	0.11	0.05	0.14	0.15
S	—	0.06	0.05	0.03	0.07	—	—	0.15	0.06	—
Σ	99.4	99.77	99.46	99.08	100.23	99.67	99.85	99.58	100.2	100.42
Sample	15426	12009	15555	15076	12052	Average	Average	71055	12038	B-1 A-35

Source: From *Taylor* (1975), Table 4.3.

This glassy material is attractive as a resource as it would require less energy to re-melt compared to a lithic fragment that would melt incrementally as each phase intersects the liquidus temperature.

Remote sensing methods have been important in understanding lunar geology, since the Apollo samples have been obtained from predominantly mare materials, and all samples have been returned from the near side of the Moon. Remote sensing data from the Apollo 15 and 16 γ-ray spectrometer missions, the recent Clementine mission, and Earth-based spectral analysis have all contributed to characterization of the global variations of chemistry on the Moon. These data have confirmed the presence of mare basaltic and highland anorthositic rock types, and have additionally provided chemical data for the distribution of Mg, Al, Ca, Ti, and Fe. It has not generally been possible to identify areas that could be utilized as enriched deposits for mineral exploitation. In contrast, the potential for subsurface water in permanently shadowed areas of the lunar south pole presents a strong driving force for further orbital imaging coupled with a surface mission in order to confirm the presence of this precious resource.

Table 3.2 Modal Mineral Abundances of the Major Minerals in Lunar Mare Basalts
(Volume Percent Normalized to 100%)

Mission Number	Basalt Type	Opaque Minerals*	Pyroxene	Feldspar	Olivine
Apollo 17	High Ti	24.4	47.7	23.4	4.6
Apollo 11	High K	20.6	57.5	21.7	0.1
Apollo 17	Low K	15.1	51.6	33.3	—
Apollo 11	Low K	14.6	50.9	32.2	2.3
Apollo 12	Ilmenite	9.3	61.1	25.9	3.6
Apollo 12	Pigeonite	9.1	68.4	21.1	1.4
Apollo 12	Olivine	7.1	53.5	19.2	20.2
Luna 16	Aluminous	7.1	51.5	41.2	0.1
Apollo 15	Olivine	5.5	63.3	24.1	7.0
Apollo 15	Pigeonite	3.7	62.5	33.8	—
Apollo 14	Aluminous	3.2	53.8	43.0	—
Luna 24	Ferrobasalt	1.8	48.6	39.1	10.4
Luna 24	Ferrobasalt (recrystallized)	1.4	60.2	34.2	4.2
Apollo 17	Very Low Ti	1.0	61.7	31.9	5.4
* Opaques are minerals that do not transmit light in thin section (e.g., armalcolite, ilmenite, spinel, troilite).					

From Lunar Sourcebook, p. 140

<u>Critical differences exist between lunar basalts and terrestrial basalts</u>. Lunar basalts crystallized and were equilibrated at oxygen fugacity values more reducing than the iron-wustite (i.e., Fe-FeO) buffer, approximately on the iron-ilmenite-ulvospinel (i.e., $Fe-FeTiO_3-Fe_2TiO_4$) buffer. Terrestrial basalts, in contrast, were crystallized and equilibrated at higher fugacity values. This quantitatively describes the more reducing conditions under which lunar materials formed compared to terrestrial materials. The net result is that lunar samples contain no Fe^{3+} but rather Fe^0 and Fe^{2+}, compared to terrestrial materials that typically contain Fe^{2+} and Fe^{3+}. The mineralogy of lunar materials is therefore different compared to terrestrial materials.

3.2   Mineral Resources

Lunar mineral resources form an important set of raw materials for In Situ Resource Utilization (ISRU) processing. On Earth, geological processes that include deposition from hydrothermal solutions have caused mineral deposits to be developed at depth, then later exposed by erosion, and ultimately concentrated by the action of water for convenient recovery in mining operations.

On the Moon, the presence of water is possibly restricted to shadowed crater regions at the lunar poles, and no evidence to date has been observed for the concentration of minerals that would typically form an ore deposit on Earth. Terrestrial steel production relies on iron ore that is enriched and thus represents an economical resource.

Orbital remote sensing data coupled with ground truth studies from the Apollo sites has confirmed that basaltic mare and anorthositic highland regions represent the two dominant compositional regions. Compositional maps for Ti and Fe generally show enrichments in mare regions. Dark mantle deposits are thought to be the surface expression of volcanic fountain deposits like the high-Ti orange glass material (see Figures 2.4 Orange Soil 74220, Figures 2.5 and 3.2). Chemical analysis of the orange soil material reveals that it is rich in titanium (8%) and iron oxide (22%). The orange soil is probably of volcanic origin and not the product of meteorite impact. From the field photograph, it is clear that the orange soil is localized in distribution and does not form an obvious large scale feature. However, high resolution orbital imaging is needed if materials are to be identified that may serve as lunar ore deposits. A survey of typical lunar regolith reveals that a significant glassy agglutinate fraction is present in many samples. This glassy material is an attractive mineral resource as the energy required for melting is less than that for crystalline material, and physical processing is all that may be required to separate this material out for subsequent use as an ore material.

Iron bearing material in the regolith consists of nanophase Fe particles, ilmenite, pyroxene, and olivine. Titanium is also present in lunar ilmenite.

Figure 3.2 Orange Soil from the Taurus-Littrow Apollo 17 Landing Site. Apollo photograph AS17-137-20990.

3.3　　　　　Lunar Highlands Rock Types

The lunar highlands are comprised predominantly of anorthosite, which is a rock made up of the mineral plagioclase feldspar. Lunar anorthosites contain the plagioclase mineral anorthite, which is the Ca and Al-rich plagioclase end-member. Three major rock types have been identified in the lunar highlands sample inventory. First are *ferroan anorthosites*, which are composed dominantly of plagioclase, and represent the oldest highland materials. These ferroan anorthosites, in addition to containing Ca-rich plagioclase, also contain olivine and pyroxene that is more Fe-rich than most of the Mg-rich crustal rocks and are so named. These materials are well represented in the Apollo 15 Genesis rock and the Apollo 16 samples, and are thought to have formed as coarse-grained intrusive rocks by flotation of plagioclase in the lunar magma ocean. Second are *Magnesium-rich rocks* that are similar to the ferroan anorthosites but contain Mg-rich grains of olivine and pyroxene, resulting in the rock varieties norite and troctolite. The modal abundance of olivine, pyroxene, and plagioclase is variable in these rocks. Thirdly, *KREEP rocks* are crystalline highland rocks that have a chemical component of enrichment in potassium (K), phosphorous (P), the Rare-Earth Elements (REE), thorium (Th), and uranium (U).

Representative bulk chemistry and modal analysis of lunar highlands rocks are listed in Tables 3.3 and 3.4, respectively. Many of the highlands rock types are present as discrete lithic fragments in lunar regolith samples, and have been analyzed from relatively small samples. However, it is clear that plagioclase-rich rock types dominate the highlands materials along with olivine, low-Ca and high-Ca pyroxene, spinel, and other minerals. The bulk chemistry of the highland rock types reflects this variation in mineralogy in the same way that the mare basalt chemistry reflects the mineralogy of the basaltic component. Photomicrographs of representative highland materials are shown in Figure 2.2.

Table 3.3 Major Element Chemistry of Highland Rock Types (Oxide Weight Percent)

Oxide	Anorthosite	Gabbroic Anorthosite	Anorthositic Gabbro	Troctolite	Low-K Fra Mauro Basalt	Medium-K Fra Mauro Basalt
SiO_2	44.3	44.5	44.5	43.7	46.6	48.0
TiO_2	0.06	0.35	0.39	0.17	1.25	2.1
Al_2O_3	35.1	31.0	26.0	22.7	18.8	17.6
FeO	0.67	3.46	5.77	4.9	9.7	10.9
MgO	0.80	3.38	8.05	14.7	11.0	8.70
CaO	18.7	17.3	14.9	13.1	11.6	10.7
Na_2O	0.80	0.12	0.25	0.39	0.37	0.70
K_2O	—	—	—	—	0.12	0.54
MnO	—	—	—	0.07	—	—
Cr_2O_3	0.02	0.04	0.06	0.09	0.26	0.18
Σ	100.5	100.2	99.9	99.9	99.6	99.4

Sources: *Reid* (1974), *Prinz et al.* (1973).

Table 3.4 Major Element Chemistry and Modal Composition of Highland Rock Types (Oxide Weight Percent and Modal Percent)

Oxide	Ferroan Anorthosite 15415, 123	Ferroan Anorthosite 67016, 326/8	Anortho-sitic Norite 15455, 9015	Norite 77215, 45	Gabbro-Norite 61224, 6	Troctolite 14321, c1020	Troctolite 76535, 21-22	Spinel Troctolite 15445, 103 A-G
SiO_2	44.1	45.3	47.7	51.3	50.7	43.0	42.9	37.5
TiO_2	0.02	0.40	0.10	0.32	0.40	0.06	0.05	0.25
Al_2O_3	35.5	26.2	27.0	15.1	13.2	28.7	20.7	14.7
FeO	0.23	6.56	2.80	10.07	9.91	2.59	4.99	6.40
MgO	0.09	5.30	6.90	12.56	12.77	9.45	19.10	33.00
CaO	19.7	15.8	14.8	9.0	11.6	15.1	11.4	4.8
Na_2O	0.34	0.28	0.440	0.430	0.910	0.379	0.200	0.140
K_2O	<0.01	0.02	0.080	0.140	0.017	0.075	0.03	0.022
MnO		0.09	0.049	0.160	0.159	0.025	0.070	
Cr_2O3		0.083	0.172	0.320	0.291	0.146	0.110	
Σ	99.9	100.1	100.0	99.4	100.0	99.5	99.6	96.8
Sample	15415	67016c	15455	77215	61224	14321, c1	76535	15445
Plagioclase	99	68-69	70-75	52	34	75	35	35
Olivine	tr					24	60	50
Opx/Pig	tr	~ 19	25-30	45	43	1	5	
High-Ca pyx	tr	~ 8	tr	1	22	0	tr	
Mg-spinel			tr					15
Cr, Fe-spinel			tr	tr	tr		tr	
Fe-Ni metal	tr		tr	tr	tr		tr	
Troilite		3-4	tr	1.5	tr		tr	
Ilmenite	tr	tr	tr	0.1				
Phosphates			tr	tr			tr	
Others	tr		tr	1			tr	tr

Sources: Data from tables A5.32, A5.33, A5.41, A5.42, and A5.43 of Planetary Materials, Lunar Samples, *Papike et. al.*, (1998)

Inspection of the bulk chemistry and modal mineralogy of highland rocks reveals that a likely candidate for a lunar highland simulant is a high-Ca anorthosite. This composition is chemically and mineralogically more simple than the mare basalts. A root lunar highland anorthosite could thus be chosen for use as a simulant, and the range of highland rock materials could be matched by addition of olivine and pyroxene. The root simulant choice for highland materials is discussed further in Section 5.0, Recommendation 1: Standard Lunar Regolith Simulant Materials.

The lunar highlands anorthosites are thought to have formed by flotation in the lunar magma ocean and for this reason are mineralogically concentrated in plagioclase, and also are chemically more simplified than the mare basalts. The few samples that represent unmodified original highland material are termed *pristine*. The highlands material has been subjected to significant meteorite bombardment and as a result has diverse textural relationships depending on the degree of melting and recombination with other mineralogical components. The terms *monomict* and *polymict* refer to the varying degree of incorporation of these other components in a rock. These distinctions are important for geological interpretation as discussed below.

3.4   Pristine Rock Types

The pristine lunar highlands samples have the highest Mg/Fe and Ca/Na ratios, and so are distinct in terms of their bulk and mineral chemistry. The ferroan anorthosites, Mg-rich rocks, and KREEP rocks are included in this pristine group; the KREEP rocks are volumetrically insignificant compared to the other rock types. Other rock types are found in the Apollo samples which represent highland material, and these include high-silica granites and alkali (Na-rich) anorthosites, which are again volumetrically less important. All of these pristine rock types are delineated on a plot of Mg/(Mg+Fe) versus Na/(Na+Ca) as shown in Figure 3.3 and exhibit a significant variation in major element chemistry that will need to be addressed in utilization of these materials for processing. This variation has implications for simulant development both in terms of bulk and mineral chemistry, but also in terms of textural features as outlined below.

3.5   Breccia Rock Types

The predominance of breccias in the Apollo inventory indicates the significant influence of impact processes on lunar regolith materials. A *breccia* consists of coarser fragments or clasts of rock, mineral, or glass, enclosed or contained in a matrix that is of a finer grain size and may be of either similar or different material. The interpretation of a breccia clearly indicates mixing of different materials by a mechanism that does not separate the materials from one another. The repeated mixing by impact processes is evidenced in lunar breccias. The Lunar Sourcebook categorizes lunar breccias as *monomict*, which are composed of a single rock type of differing sizes, and *polymict*, which are composed of numerous rock types. These polymict breccias are further subdivided into *fragmental breccias*, *glassy melt breccias*, *crystalline melt breccias*, *clast-poor impact melts*, *granultic breccias*, *dimict breccias*, and *regolith breccias*. These classifications are important for geological interpretation and serve as an indication of the importance of the rock type for simulant discussion and anticipation of the variety of materials to

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Figure 3.3 Bulk-Rock Na/(Na + Ca) Versus Mg/(Mg + Fe), Mole Ratios, for a Variety of Pristine Highland Igneous Rocks (After *Warren*, 1986). Dashed field (lower right) encompasses 19 troctolites. The ferroan anorthosites (lower center) have distinctive, low Mg/(Mg + Fe), low Na/(Na + Ca) compositions.

be expected for lunar surface activities. Photomicrographs of representative lunar breccias are shown in Figure 2.3.

3.6   Origin and Characteristics of Lunar Regolith

The nature of the lunar surface is summarized in Chapter 4 of the Lunar Sourcebook. In terms of the appearance of the lunar surface, meteorite impact processes have produced the heavily cratered terrain on the lunar surface, and have caused mixing of rocks from mare and highland environments and modification of mineralogy due to both physical and chemical effects. The surface topography presents a significant challenge to lunar exploration, and indeed limited the Apollo missions to mare regions and locations that were proximal to highland terrain. For this reason, little direct highland material has been sampled and studied, and our knowledge of highland geology is based on representation of anorthositic components in regolith from mare regions. Meteorite impact events have caused crushing of rock and mineral grains (which exhibit shock features), impact melting, evaporation, and condensation. These processes have resulted in the production of nanophase iron that can be used to measure the degree of maturity of a soil from the concentration of these particles.

The Moon has no atmosphere and surface materials are in a hard vacuum on the order of 10^{-12} Torr. Exposure of surface grains to the solar wind has also resulted in damage to minerals and implantation of species into the mineral surfaces. Large temperature variations are observed between the lunar day and night. Electrostatic levitation of lunar dust was observed by Apollo astronauts and has been documented by photographs of the lunar horizon against the black sky. It is generally considered that electrostatic levitation occurs by the terminator as it moves across the lunar surface. However, this phenomenon was not observed by the two Russian Lunokhod robot vehicles, and merits further study. Also, this presents a significant material issue on the lunar surface of dust abrasion and contamination of equipment and astronaut EVA suits.

It is the source materials from mare and highland terrains coupled with impact processes and other modifying forces that must be addressed in the development of lunar simulant materials. The closeness of match between terrestrial simulant materials and the lunar regolith that they simulate is the degree of fidelity of the simulant. High fidelity simulants thus represent a challenge in duplicating compositional and textural features, whereas low fidelity simulants are less challenging as they may only address a subset of features.

3.7 Geotechnical Properties

The lunar regolith has been studied extensively both in terms of material sampled by the Apollo and Luna missions directly, but also by remote sensing and other techniques. Great emphasis has been placed on engineering studies as these data were critical for the success of the Apollo missions, and indeed will be critical for upcoming lunar exploration missions. While the study of Apollo samples has included geological, mineralogical, and geochemical analysis, these studies have primarily been focused on understanding the Moon and improving our models of planetary geology.

Geotechnical measurements were accomplished using in situ measurements on the Moon and extensive analysis of the Apollo samples upon their return to Earth. These studies are covered extensively in chapter 9 of the Lunar Sourcebook and will be summarized here. Two types of geotechnical data are available, those that represent data specific to a soil material and those that are characteristic of the soil in place on the Moon and are therefore a function of the degree of packing (see Table 2.1). It is the former that are most germane to the development of lunar simulant materials. However, the ability to simulate in situ soil properties is also important. Simulants need to be packed so that the same density state and behavior are obtained compared to the lunar regolith.

The lunar regolith is composed of five basic particle types: crystalline rock fragments, mineral fragments, breccias, agglutinates, and glasses. The composition of lunar regolith samples is more limited than terrestrial materials due to the more diverse geological environments and processes on Earth, and the predominance of impact processes and the lack of water and recycling processes on the Moon. Impact processes on the Moon have reached a steady state with regards to soil thickness, grain size distribution, and other properties. It is the grain size distribution that controls the dominant physical nature of the regolith, such as strength and compressibility, as well as optical, thermal, and seismic properties.

Grain size distribution data are typically plotted in terms of grain size or φ value, where φ = -log$_2$ d, and d is the particle diameter in millimeters. The grain size distribution is plotted as φ versus the cumulative percent. The shape of the size distribution curve and numerous descriptive parameters are used to quantitatively describe the grain size distribution.

A typical plot of this type is shown in Figure 3.4 which illustrates the grain size distribution for Apollo 17 soils, and demonstrates the general consistency of grain size data for a given Apollo site. The particle size data are shown for splits of Apollo 17 lunar soil sample 78221,8 which was analyzed by three laboratories. The lower horizontal axis shows particle size as φ, and the upper horizontal axis shows particle size in micrometers. The vertical axis plots the cumulative percent on a probability scale.
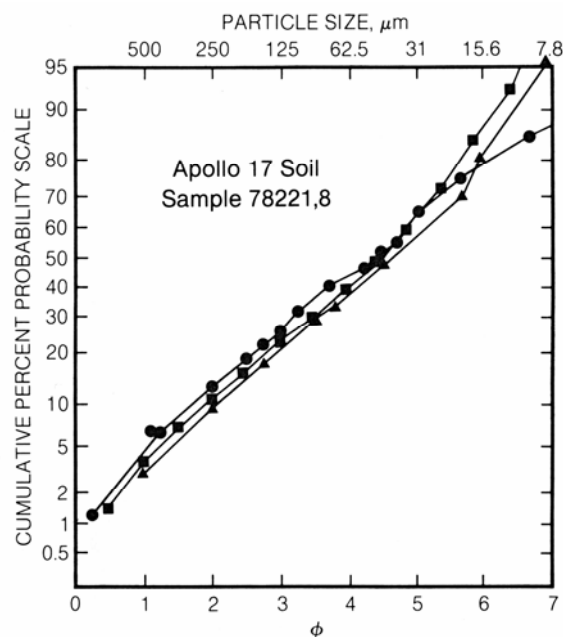
Figure 3.4 Particle Size Distribution from Apollo 17 Lunar Soil Samples
From unpublished data (after B*utler and King* 1974).

Figure 3.5 indicates the upper and lower bounds of lunar grain size data for all Apollo sites. Lunar soils generally group in a narrow band on these plots, thus making the grain size distribution curve attractive as a first-order physical property for the purposes of simulant development. The median particle size is between 40 to 130 μm with an average value of 70 μm, so that approximately half of the soil is composed of particles that are very fine in size, much finer than terrestrial beach sand, for example. This large dust fraction dominates discussion of the physical behavior of the lunar regolith.
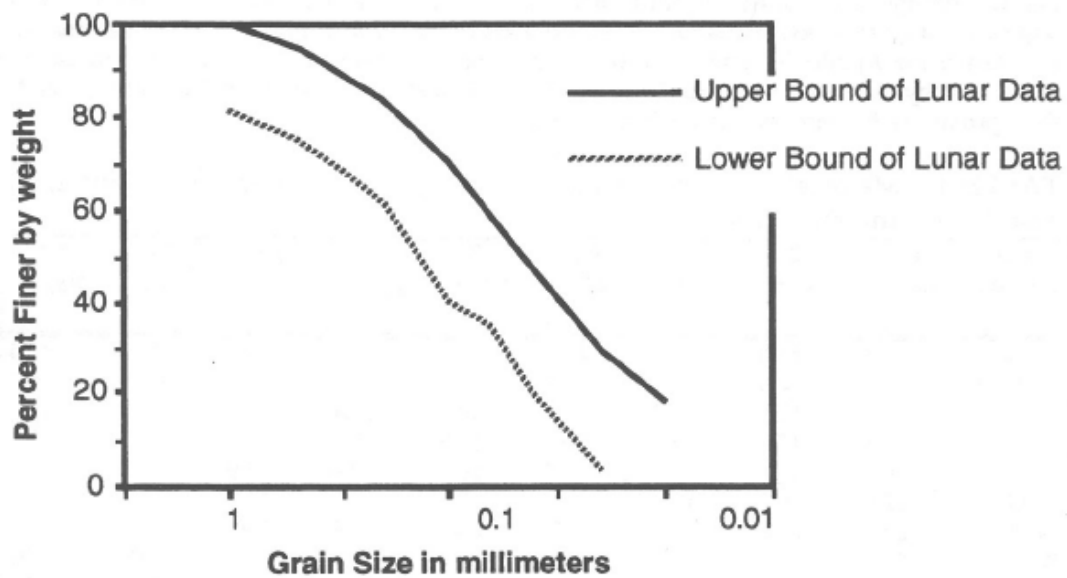
Figure 3.5 Grain Size Limits for all Apollo Lunar Soils (Note Reversed
Grain Size Scale on X-Axis; Modified from *Carrier, et al.*, 1973).

Grain shape and **grain shape distribution** data have a strong influence on the geotechnical behavior of the soil. The grains are typically elongate and subangular to angular in shape, and this elongation permits the grains to pack tightly under compressive loads as well as the daily effect of lunar tidal earthquakes. The underlying soil, which has been compacted in this way, is capable of remarkable geometries for slope stability compared to terrestrial soils, allowing the lunar soil to be excavated to form a trench with unusually steep sides (*Carrier et al.,* 1991). Other shape factors that have been evaluated for lunar materials are aspect ratio, roundness, and the resulting effect on volume coefficient and specific surface area.

Bulk properties of lunar soil have been well studied, including **specific gravity** and **bulk density** (see Table 2.1). Density data are of great importance for engineering evaluation and in preparation for missions. The Lunar Sourcebook lists a recommended value of 3.1 g/cm^3 for the specific gravity of lunar soil. Specific gravity is a function of the proportions of the rock and mineral components making up a given soil and enclosed voids that are characteristic of lunar materials. The bulk density is the traditional mass per unit volume of lunar soil. The in situ bulk density of lunar soil was estimated by various methods (see the Lunar Sourcebook, pp. 483-485) and comparisons of this parameter have previously been made to an unspecified lunar simulant material (i.e., crushed basaltic lava, Lunar Sourcebook, p. 485). Corrections were made for differences in the grain size distribution and terrestrial versus lunar gravity. SLRS materials that have a traceable set of physical and chemical characteristics will improve our ability to correlate terrestrial and lunar soil behavior. Other bulk properties of the lunar regolith are based on in situ properties, such as density variation with depth, and are less applicable to simulant discussions.

Three important properties with respect to engineering data are **compressibility**, **shear strength**, and **permeability** (see Table 2.1). Compressibility refers to the volume change that occurs when a confining stress is applied to a soil. Shear strength can be described in terms of cohesive and frictional components and is important for evaluation of bearing loads. Permeability is a measure of the ability of a fluid to flow through the soil matrix. As these and other related properties are a function of the degree of compaction or arrangement of soil particles, they are also less applicable to simulant discussions. However, these properties were discussed by workshop attendees and figure prominently in assessment of properties that define requirements for activities, and can generally be achieved through simulating mineralogy and grain size, shape, and distribution characteristics.

Trafficability is the ability of a soil to support a vehicle and to provide traction for movement. Development of the LRV and experiences with the martian rovers attest to the importance of trafficability, and the need to have extensive testing using simulant materials for both the development process and during troubleshooting when the vehicle encounters unexpected soil conditions and loses traction. These traction issues highlight an additional need for simulant use as an important component of the response network for real-time problem solving.

Bulk electromagnetic properties of the lunar regolith are important for applications such as Ground Penetrating Radar (GPR) where it is anticipated that penetration of more than 100 m is possible, but is limited by electromagnetic scattering. GPR is an attractive candidate for subsurface feature detection and may be instrumental in identifying buried lunar lava tubes for possible habitat use. Remote sensing techniques using optical astronomy and radar imaging also depend on light scattering and electromagnetic properties of the soil, respectively, and are obviously important components of planetary imaging programs. The martian soil simulant Mars-1 was selected primarily using spectral data as compared to the bright regions of Mars. Simulant Mars-1 does not match the mineralogy and chemistry of martian soils, based on existing data from Mars missions (*Foley et al.,* 2003). It is therefore important to perform comparisons using electromagnetic response data but also is critical to incorporate compositional data in simulant matching strategies.

Photoconductivity of lunar soils is an important parameter in the study of electrostatic charging and dust movement. Large changes are observed in electrical conductivity of lunar dust following exposure to visible and ultraviolet (UV) radiation. Apollo astronauts observed and photographed dust that was visibly levitated against the horizon and the movement of dust with the terminator raises concerns for long term missions that have experiments or processes that are vulnerable to dust problems. The relative dielectric permittivity of lunar soils is dependent on density, and the loss tangent is dependent on density, composition and temperature. The compositional variation via density is a function of the sum $TiO_2 + FeO$; this dependence with that of temperature are important for remote sensing applications that map composition and temperature variations over the lunar surface. Both lunar samples and simulant analysis can support research in this area.

The most important data from the perspective of simulant development are grain size distribution curves as this is the primary feature that must be approximated. Evaluation of geotechnical properties by the 2005 Workshop participants also placed grain shape at a high priority in

simulant development, but it was generally recognized that this property may require special grinding or other processing in order to produce elongated grains.

Analysis of the mineralogy at a given size fraction has revealed the relationship between agglutinates, grain size, and soil maturity, thus highlighting the important connection between physical and mineralogical properties.

3.8   Lunar Samples

As discussed, the lunar samples were returned primarily by the Apollo missions, and have been the subject of ongoing research since the early 1970s. The main emphasis of analysis of these materials has been to better understand the geology of the Moon, as well as many derivative studies that include engineering analysis.

3.8.1   The Apollo Sample Inventory

The Apollo samples are made up of a variety of igneous rock types that differ markedly in both chemistry and mineralogy. The two primary materials represented are dark basaltic lunar mare material and lighter-colored feldspar-rich anorthositic rocks from the lunar highlands (see Figure 2.1 through 2.5). The lunar regolith represents the spectrum of compositional and mineralogical sampling from these two materials which have been modified both physically and chemically by impact processes. Figure 3.6 demonstrates how the lunar regolith can be described by a mixture of varying amounts of mare basalt and highland anorthosite along with an approximately constant proportion of impact melt glass. Relative proportions of fragments of mare rocks, highlands rocks, and glass in the 0.1 to 1-mm fraction of the lunar regolith are shown for Apollo (A) and Luna (L) sites. Apollo 11 and 12, and Luna 16 and 24 sites are dominated by mare materials, Apollo 16 samples are dominated by highland materials, and other sites vary depending on their proximity to mare/highlands boundaries.

Table 3.5 lists major element compositions for the Apollo "reference suite" soils. The variation in bulk chemistry reflects the proportions of materials from mare and highland sources as illustrated previously. Mare basalts contain higher concentrations of FeO and TiO_2 and have higher CaO/Al_2O_3 ratios (but lower total content of CaO and Al_2O_3) than do highland rocks, reflecting the lower proportion of plagioclase feldspar in the mare basalts. These compositional differences are central to the first-order identification of lunar simulant materials, as the chemistry is more easily treated in data sets. However, the bulk chemistry depends on the mineral chemistry, which is ultimately more important for discussions of simulant materials.

From consideration of the range of compositions sampled at the Apollo sites, and also from orbital data, it has been possible to calculate average values for mare and highland materials. These data are listed in Table 3.6, and can be used to contrast these two source materials. However, it is important from the perspective of simulant development to adequately anticipate the range of chemistry, physical properties, and mineralogy that may be expected at lunar landing sites. The use of averaged data for lunar materials should be made cautiously.

COMPONENTS IN THE LUNAR REGOLITH
(FUSED-SOIL-FREE; 0.1 TO 1 MM FRACTION)
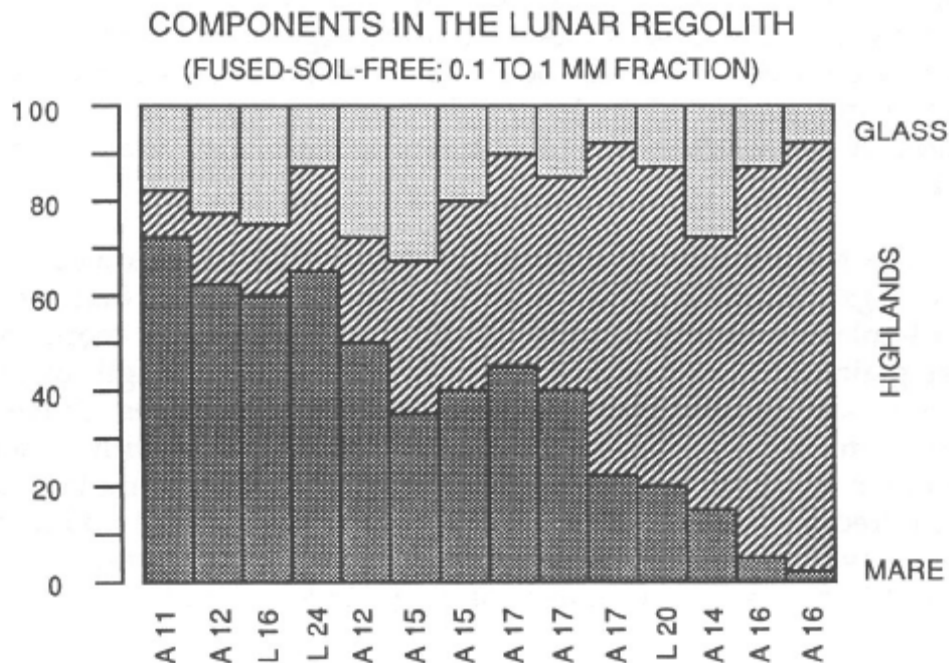
Figure 3.6 Components of Lunar Regolith (Modified from *Papike, et al*., 1982). Shaded regions indicate the modal proportions of glass, highlands, and mare material in the lunar regolith from the Apollo and Luna sample sites.

Table 3.5 Major Element Compositions of "Reference Suite" Soils from the Apollo Landing Sites (Values Given in Weight Percent)

Apollo Sample	11 10084	12 12001	12 12033	14 14163	15 15221	15 15271	16 64501	16 67461	17 70009
SiO_2	41.3	46.0	46.9	47.3	46.0	46.0	45.3	45.0	40.4
TiO_2	7.5	2.8	2.3	1.6	1.1	1.5	0.37	0.29	8.3
Al_2O_3	13.7	12.5	14.2	17.8	18.0	16.4	27.7	29.2	12.1
FeO	15.8	17.2	15.4	10.5	11.3	12.8	4.2	4.2	17.1
MgO	8.0	10.4	9.2	9.6	10.7	10.8	4.9	3.9	10.7
CaO	12.5	10.9	11.1	11.4	12.3	11.7	17.2	17.6	10.8
Na_2O	0.41	0.48	0.67	0.70	0.43	0.49	0.44	0.43	0.39
K_2O	0.14	0.26	0.41	0.55	0.16	0.22	0.10	0.06	0.09
MnO	0.21	0.22	0.20	0.14	0.15	0.16	0.06	0.06	0.22
Cr_2O_3	0.29	0.41	0.39	0.20	0.33	0.35	0.09	0.08	0.41
Σ	99.8	101.0	100.8	99.8	100.5	100.4	100.3	100.8	100.5

Sources: *Laul and Papike* (1980), *Laul et al.* (1978).

These differences in mineralogy are also responsible for the differing albedo of the mare basins compared to the ancient cratered highlands. Four distinct types of rocks, exclusive of these compositional differences, are observed in lunar samples. These are (1) basaltic volcanic rocks, including lava flows and pyroclastic rocks; (2) pristine rocks from the lunar highlands; (3) complex polymict breccias that include physical mixing, shattering, and melting features, and (4) the lunar soil, which is the < 1 cm portion of the lunar regolith (see Figures 2.1 through 2.5). These rocks were produced by igneous processes and are comprised of minerals that represent crystal growth from a magma but have been overprinted by the features of impact processes.

Table 3.6 Average Chemical Composition of Lunar Surface Regolith
(Oxide Weight Percent)

Oxide	Maria	Highlands
SiO_2	45.4	45.5
TiO_2	3.9	0.6
Al_2O_3	14.9	24.0
FeO	14.1	5.9
MgO	9.2	7.5
CaO	11.8	15.9
Na_2O	0.6	0.6
K_2O	—	—
Σ	99.90	100.0

Sources: From *Taylor* (1975, Table 3.2), after *Turkevich* (1973).

3.8.2   Collection, Transport, and Curation

During the Apollo missions, the astronauts collected several types of samples on the lunar surface as follows. A *contingency sample* was collected from the surface layer of soil soon after landing on each mission, and a *bulk sample* that grouped rock and soil material together was obtained only at the Apollo 11 site. *Documented samples* were specific rock or soil samples with associated sampling information including a photograph (Figure 3.7 and Figure 3.8), while *selected samples* did not include a documentary photograph. *Rake samples* were comprised of rocks sifted from the surface regolith (Figure 3.9), and *core samples* obtained with coring drills and tubes, provided cross-sections of the lunar regolith with depth. The diversity of rock sizes and topographic variations made sampling a challenge for the astronauts.

The lunar samples were transported to Earth in containers that were intended to preserve them in their original vacuum environment and isolate them from any terrestrial contaminants upon return. The rock samples generally have been well isolated from the effects of the Earth's atmosphere, while in contrast the lunar soil samples were compromised by failures of the seals in the sample boxes upon return to Earth. The dust was able to migrate through the seal boundary during sampling, which illustrates the kind of problems to be expected when dealing with lunar dust.

Figure 3.10 is a photograph taken moments after Sample Rock Container (SRC) No. 10 was opened in a vacuum chamber at the Lunar Receiving Laboratory (LRL) in Houston, Texas. The box contains a large rock, several documented sample bags with the fold-over aluminum tabs, and a 4 cm drive tube at the rear. Figure 3.11 is a close-up view of the indium seal on Apollo 16, SRC 1009. The rock box is full of documented sample bags and the aluminum tab on one of the bags was entrapped in the knife-edge and indium seal; thus, the seal was not good. One of the fluorosilicone o-rings, dark in color, is visible just outward on the indium seal.

The lunar samples are under the curation of JSC where they are kept in appropriate storage containers and are viewed and processed in glove boxes. The curation of these materials is an important aspect of lunar science for record keeping and sample identification purposes. Many samples have been subdivided and it is thus necessary to track the disassembly of rock samples over time. Despite the view held by some that the moon is made of green cheese, none of these samples have been pasteurized.

3.8.3   Availability and Research Use of Lunar Samples

Researchers entering the field of space exploration who are unfamiliar with the nature of the lunar samples typically wonder why these materials are not made available for testing purposes. Quite simply, the lunar sample inventory is priceless, and only limited quantities are made available for well planned research. The lunar samples are not available for indiscriminate destructive testing. Access to lunar samples is granted by the lunar sample curator based on a well defined and peer-reviewed research plan and samples are not loaned indiscriminately. Samples are, however, available for educational institutions to borrow for students to study. Some lunar materials have been archived in anticipation of future development of techniques that deserve the most pristine samples.

Proposals that result in the consumption of lunar samples are approved only after all other avenues of material use have been explored. This means that terrestrial materials must be utilized for the development phase of a research program where there is modification of the sample, such as melting in a furnace for crystallization studies. Ultimately, there are needs for use of lunar samples and a remarkable program of scientific investigation has resulted from their use. Geological methods have advanced due to improvements in technique and instrumental design as a direct result of lunar sample study. The lunar sample collection cannot address the testing needs of the community at large, and the solution resides with the use of SLRS materials.
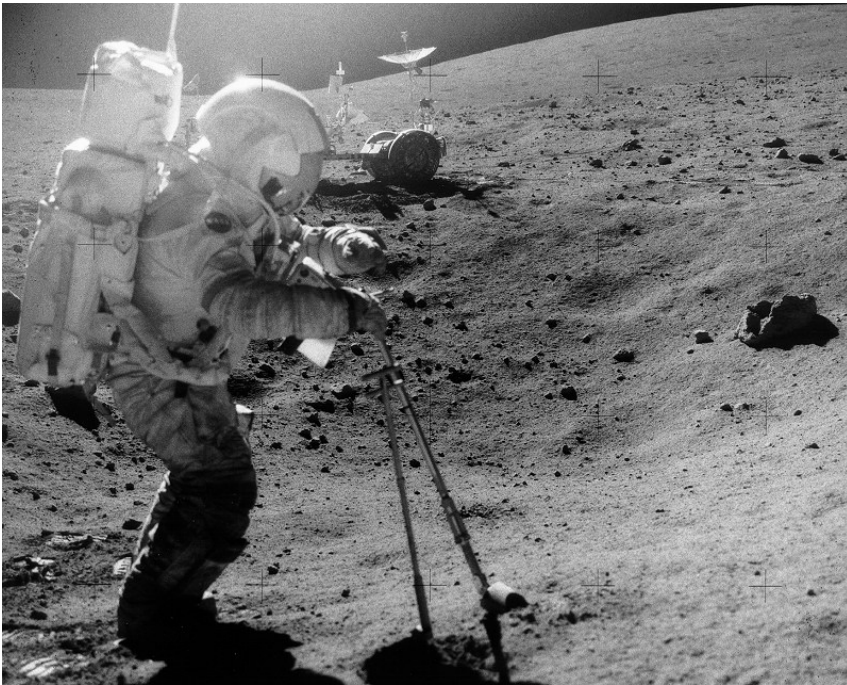
Figure 3.7 Collection of a Lunar Soil Sample at Station 6 on the Apollo 16 Mission. Apollo 16 Photograph AS16-108-17629

Figure 3.8 Soil and Rock at Station 4 of Apollo 16 Mission, with Documentation Equipment. Apollo 16 Photograph AS16-107-17445

Figure 3.9 Collection of a Rake Sample on the Apollo 16 Mission. Apollo 16 Photograph AS16-116-18690

Figure 3.10 Apollo 16 Rock and Soil Samples, and Sample Bags. NASA Photo S72-36984

Figure 3.11 SRC 1009 Indium Seal from Apollo 16. NASA Photo S72-37750

4.0   LUNAR SIMULANT MATERIALS: HISTORICAL DEVELOPMENT, PRESENT STATUS, AND FUTURE NEEDS

This section summarizes the historical development of lunar simulants, the present status of these simulants, and the requirements for simulants that are needed to support lunar and martian exploration. Past development of lunar simulants was primarily oriented towards engineering support for lunar missions and did not anticipate such processes as extractive metallurgy or volatile extraction. These simulants are currently not available in quantities necessary for science and engineering studies, and there is a strong need for redeployment of simulant JSC-1 as well as development of new simulant stocks. Future lunar and martian activities will depend critically on the existence of standard simulant materials.

4.1   Historical Development of Lunar Simulant Materials

4.1.1   Apollo LSS

Prior to the return of lunar samples during the Apollo missions, it was necessary to make a quantitative evaluation of the lunar regolith from an engineering perspective in order to plan for mission activities. During the development of the LRV, returned samples of the lunar regolith were analyzed, but due to their precious nature and limited availability for testing purposes, it was apparent early on that lunar simulants would be required for both development and flight certification purposes. The Apollo Program assigned a team of geologists and soil engineers to evaluate lunar soil data and develop criteria, which would allow the manufacture of lunar soil simulants using terrestrial materials. That expert group established five such lunar soil simulants, LSS-1 through LSS-5. LSS-4 most closely duplicated the expected soil conditions at the Apollo 15 site. LSS simulants were all crushed basalts procured from the Basalt Rock Company in Napa, California. The literature describing these materials is scarce and incomplete. It indicates that they included a S*tandard Basalt*, a S*tandard High Density Basalt*, and a *43% Vesicular Basalt* (*Mullis*, 1971). These basaltic materials were prepared following specific procedures to transform them into the LSS materials with known soil characteristics. These extensive preparations included exhaustive characterization of the soils before and during tests including maintaining soil cohesion and moisture content. Other materials, such as Yuma sand, were also characterized, standardized, and used in comparative tests for the LRV wheel design development phase performed through collaboration between MSFC, the U. S. Army Engineer Waterways Experiment Station, and a team lead by Boeing. Personal communications with Apollo test engineers indicate that approximately 35 simulants were used in the program but no literature has been found to corroborate this. It is possible that such a statement refers to the different soils prepared for testing using the lunar soil simulants. The LSS materials are no longer available and their exact properties are not well documented, but they demonstrate that the use of standard simulant materials by lunar surface hardware development engineers contributed to the historical success of the lunar missions. In the post-Apollo era, the LSS simulants have been referred to indiscriminately as Napa Valley Basalt simulant (NVB). A limited amount of this simulant still exists, but is not likely to be utilized again (NVB may in fact

be andesitic in composition and may be more appropriate for use as a martian simulant due to similarities with some areas of the martian surface).

4.1.2 Lunar Simulants MLS-1 and JSC-1

Lunar simulants JSC-1 and MLS-1 are terrestrial materials of basaltic composition that were chosen based on matches of their bulk chemistry to Apollo regolith compositions. Minnesota Lunar Simulant (MLS-1) was produced in the 1970s, and JSC-1 was produced in the 1990s. These terrestrial materials were selected by comparison of their bulk chemistry with targeted lunar soil chemistry, and specifically target lunar mare basalts of differing composition. Lunar mare simulant MLS-1 matches the composition of a high-Ti Apollo 11 basalt, and JSC-1 matches an average Apollo 14 mare basalt (see Tables 4.1 and 4.2 and Figures 4.1 and 4.2).

Table 4.1 Comparison of JSC-1 and MLS-1 with Targeted Apollo Composition (Values in Oxide weight percent)

Oxide	JSC-1	Apollo 14 Average Soil		MLS-1	Apollo 11 Soil 10002
SiO_2	47.71	48.1		43.9	42.2
TiO_2	1.59	1.7		6.30	7.8
Al_2O_3	15.02	17.4		13.7	13.6
Cr_2O_3	0.04	0.23			0.30
Fe_2O_3	3.44			2.60	
FeO	7.35	10.4		13.40	15.3
MnO	0.18	0.14		0.20	0.20
MgO	9.01	9.4		6.70	7.8
CaO	10.42	10.7		10.10	11.9
Na_2O	2.70	0.70		2.10	0.47
K_2O	0.82	0.55		0.20	0.16
P_2O_5	0.66	0.51			0.05
LOI	0.71				
Total	99.65	99.8		99.20	99.9
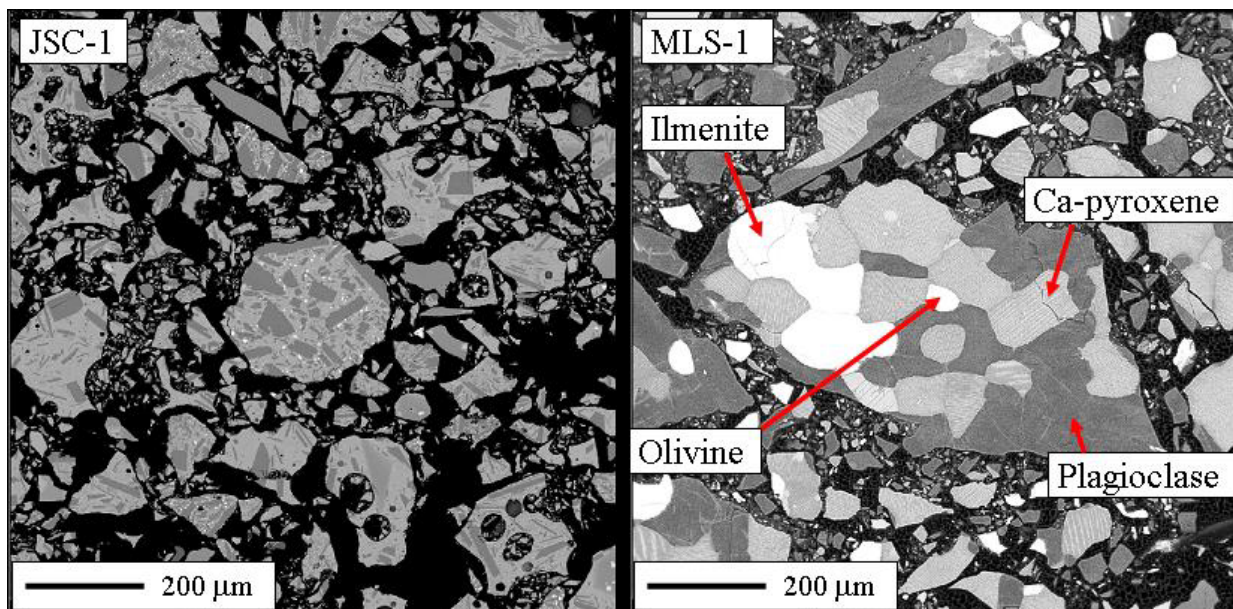
Figure 4.1 Lunar Simulants JSC-1 and MLS-1. Backscattered-electron images obtained on polished grain mounts of JSC-1 and MLS-1 simulant using the electron microprobe (stage mapping with effective 100X magnification). The contrast function of a backscattered-electron image is due to atomic number contrast, so that ilmenite is brighter than plagioclase due to compositional differences. Note the coarse grain size and large constituent minerals in grains of MLS-1 compared to JSC-1. Monomineralic grains in MLS-1 are of similar size to lithic grains in JSC-1 but are typically composed of individual plagioclase, ilmenite, and pyroxene crystals. MLS-1 simulant shown here has not been reground to improve grain size match to Apollo soils.
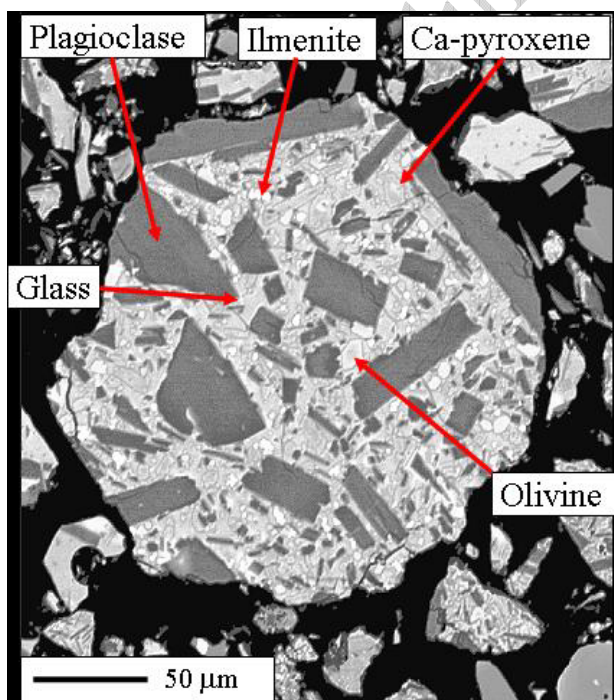
Figure 4.2 Lunar Simulant JSC-1. Backscattered-electron image at 300X magnification. Compare crystal size of lithic fragments of JSC-1 and MLS-1 with Figure 4.1. JSC-1 exhibits plagioclase phenocrysts and fine grained matrix of olivine, Ca-pyroxene, ilmenite, and glass. Smaller grain sizes are typified by lithic fragments and monomineralic grains dominated by plagioclase.

Table 4.2 Mineral Chemistry of MLS-1 and JSC-1 Lunar Mare Simulants

Mineral	JSC-1	MLS-1
Plagioclase	$An_{64-71}Ab_{28-33}Or_{1-3}$	$An_{44-50}Ab_{46-60}Or_{3-5}$
Olivine	Fo_{82-86}	Fo_{48-51}
Ca-pyroxene	$Wo_{45}En_{34-38}Fs_{17-21}$	$Wo_{39-41}En_{39-41}Fs_{19-22}$
Ilmenite	$Fe^{2+}_{0.85}Fe^{3+}_{0.09}(MgMn)_{0.103}(AlCr)_{0.0025}Ti_{0.95}O_3$	$Fe^{2+}_{0.95}Fe^{3+}_{0.0875}(MgMn)_{0.075}(AlCr)_{0.0025}Ti_{0.95}O_3$
Magnetite-Ulvospinel	Not present	$Fe^{2+}_{0.22}Fe^{3+}_{2.05}(MgMn)_{0.03}(AlCr)_{0.12}Ti_{0.25}O_4$
Other phases present	Chromite, Clay, Cristobalite? Magnetite?, Hematite?	
Analyses by electron-probe microanalysis and recalculated to mineral end-member components for formula representation. Data from *Carpenter* (2005).		

4.1.3   Minnesota Lunar Simulant MLS-1

In the late 1980s, MLS-1 was produced from an intrusive igneous rock of gabbroic composition and obtained from an abandoned quarry in Duluth, Minnesota. The bulk composition of MLS-1 is similar to high-Ti mare basalts from the Apollo 11 site (see Figure 4.3). MLS-1 contains coarse grains of plagioclase, olivine, ilmenite, titanomagnetite, and clinopyroxene grains that exhibit orthopyroxene exsolution lamellae. This rock was mined and crushed in order to achieve the grain-size distribution that is appropriate for lunar regolith material (see Figure 4.4). MLS-1 was milled to produce the appropriate grain size characteristics of an Apollo 11 soil, and although the distribution curve is similar, the grains at a given size fraction are monomineralic rather than containing lithic fragments as would be expected for a volcanic rock. That is, the coarse grain size contains monomineralic grains of single mineral species, such as ilmenite, when at the same size in an Apollo soil one observes complex materials such as agglutinates and lithic fragments. <u>The implication of this difference is that the microscopic properties are defined by monomineralic minerals rather than rocks, and a critical component of lunar soils, the glassy agglutinate fraction, is completely absent in MLS-1 due to its formation as an intrusive igneous rock</u>. One would expect the partial melting behavior of MLS-1 to deviate significantly from that of Apollo soils due to dependence on melting of mineral components rather than glass particles. For a melting process where the first produced melt is segregated for further processing, very different melt chemistries would result for MLS-1 compared to a lunar soil. It should be noted that a grain size distribution curve does not specify the modal mineralogy at each size category, so matching terrestrial materials to lunar regolith based solely on size distribution forms only the physical portion of the simulant.
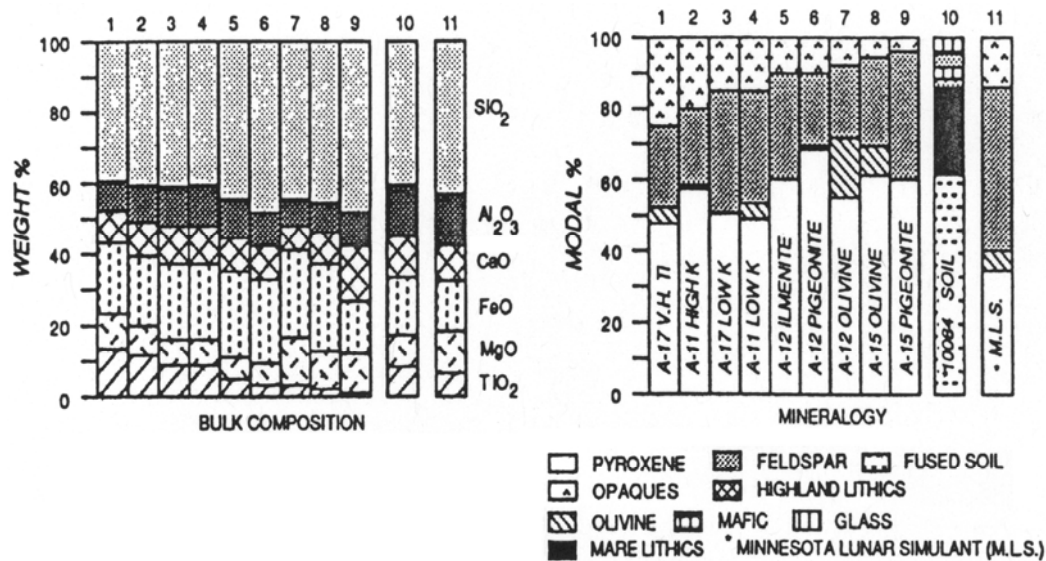
Figure 4.3 Comparison of Mare Basalts, Mare Soil 10084, and MLS-1. Left chart compares bulk chemistry of Apollo mare basalts with MLS-1 (values in oxide weight percent), and right chart compares modal composition of mineral and rock components (values in modal percent). Sample labeling (Sample 1 is A-17 V.H. Ti, etc.) in right chart applies to left chart. Modal components are shown below right chart. (*Weiblen and Gordon*, 1988).
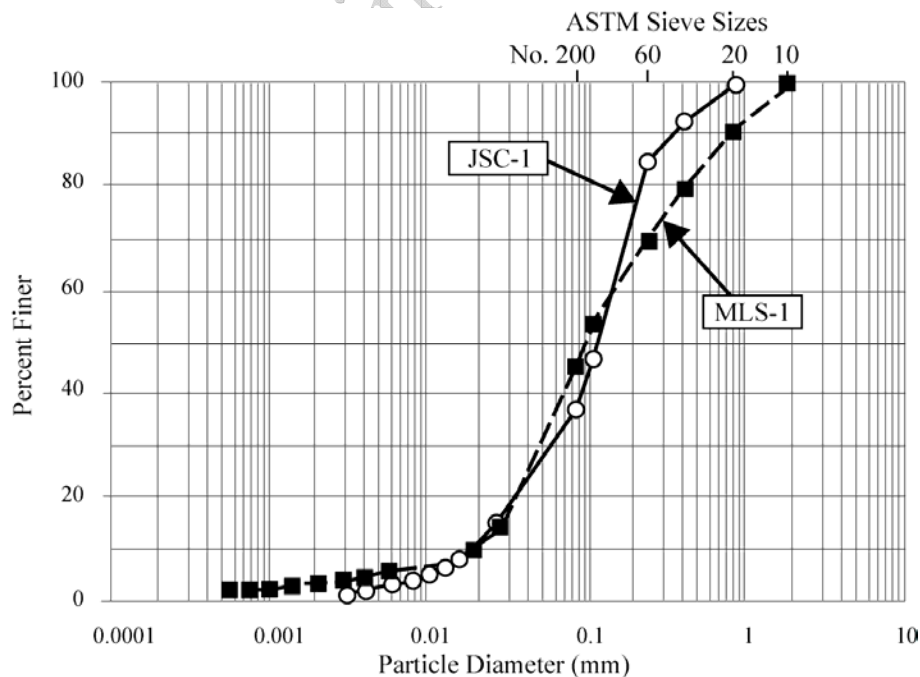
Figure 4.4 Grain Size Distribution of MLS-1 and JSC-1 (*Perkins and Madson*, 1996).

MLS-1 is a good example of what is both desirable and undesirable with regard to use of terrestrial source materials and the processing methods that are used to produce a simulant. It is attractive due to the high Ti content and specifically targets high-Ti lunar basalt as MLS-1 contains a relatively high amount of ilmenite. Terrestrial basalts do not generally exhibit elevated Ti content so the number of potential source localities is limited. The coarse grain size of MLS-1 is a good match for the more coarsely crystalline lunar basalts.

There are, however, several less desirable features. An intrusive igneous rock has crystallized over a longer time period compared to a volcanic rock, and thus contains larger mineral grains formed by slow crystal growth and contains no glassy phase. In addition to these characteristics, MLS-1 additionally exhibits features such as exsolved orthopyroxene in a clinopyroxene host that formed by slow subsolidus cooling. It also contains titanomagnetite which reflects the more oxidizing conditions during crystallization. Lunar basalts, in contrast, formed under more reducing conditions and do not contain a magnetite phase.

Simulant MLS-1 is an intrusive igneous gabbro that has a significantly larger mineral grain size than a volcanic ash. The coarse grain size of MLS-1 is problematic for comparison with a fine-grained basalt, because as the material is milled and crushed to make the necessary dust component for a simulant, rock (i.e., multimineralic or lithic) fragments break down and liberate large mineral fragments. This is in contrast to volcanic materials where the fine grain sizes contain lithic fragments. Lunar soils contain lithic fragments down to essentially the dust size fraction. At the grain size that would still exhibit lithic fragments in a lunar soil, MLS-1 material is populated by large monomineralic fragments. The implications of this are twofold. First, the physical behavior of the simulant will depend in part on mineral fragments rather than lithic fragments, and secondly, the melting behavior of the simulant will reflect melting of pure mineral grains rather than an assemblage that would likely melt at a different temperature.

These aspects are problematic for use in both chemical and physical processing experiments and testing regiments. An additional problem with MLS-1 is that the grain-size distribution of previously produced material has a fraction of larger grains that is too great and will require regrinding by researchers in order to bring the distribution into agreement with Apollo soils.

The sampling problems and chemical variability associated with improper sampling are discussed in Section 4.12, Standardization and Traceability of SLRS Materials. A final issue with MLS-1 is that the material was obtained from a now abandoned quarry. It is always desirable to utilize an active quarry where assistance from a mining operation is available and fresh rock material is guaranteed. While MLS-1 has enjoyed success as a simulant material, these are valid criticisms that will need to be addressed in future simulant development and serve as lessons learned.

4.1.4 Lunar Mare Basalt Simulant JSC-1

In the late 1980s, discussions began that recognized the need for lunar simulants that would address needs for both mare and highland activities and the need for a material that would serve to support a variety of scientific and engineering tests. The production of lunar mare simulant JSC-1 was initiated for the purposes of lunar EVA suit development at JSC. Volcanic ash of a

basaltic composition was obtained from a cinder ash quarry located on the flank of Merriam cinder cone in the San Francisco Volcanic Field near Flagstaff, Arizona.

The JSC-1 ash is similar in bulk composition to low-Ti lunar mare basalts from the Apollo 14 site (Table 4.1). The basalt from this locality is an extrusive volcanic airfall ash that contains vesicular cinders and glassy quench material due to the rapid cooling during eruption. The mineralogy of JSC-1 includes plagioclase, olivine, pyroxene, ilmenite, and basaltic glass. The degree of oxidation during cooling is very minimal in volcanic ash compared to the gabbro from which MLS-1 was derived. JSC-1 was milled and crushed in order to achieve the grain size distribution of typical lunar soils (Figure 4.4). If the grain size distribution curves for MLS-1 and JSC-1 are compared, similarities and differences are highlighted. These curves illustrate the coarse grain size issue with MLS-1, but also demonstrate a good duplication of the lunar grain size variation. Note that the MLS-1 grain-size distribution shown in Figure 4.4 pertains to material that was reground in order to improve agreement with Apollo soils and is not the distribution MLS-1 simulant. The distribution MLS-1 simulant thus requires further grinding prior to use. Of all the physical properties of lunar soils, it is the grain size variation that is most straightforward to produce in a simulant, with other properties such as grain shape and oxidation state being more difficult to produce in a root simulant, as will be discussed.

Compared to MLS-1 that has been reground, simulant JSC-1 is a better match to a lunar soil in terms of texture and mineralogy. JSC-1 is a volcanic ash which contains glassy material and is therefore a better approximation to lunar regolith which contains agglutinates. As stated previously, JSC-1 is an Apollo 14 mare simulant of intermediate composition in terms of Ti, Ca, Al, K, and P. JSC-1 can be utilized in studies that require a simulant that represents an average of both mare and highlands material. While JSC-1 does not represent a root mare simulant that is an end-member, it is of interest as a simulant source due to its availability in addition to the compositional and mineralogical features.

About 12,000 kg of JSC-1 simulant was produced in the early 1990s and has been widely distributed to NASA sponsored projects, academic researchers, and the educational outreach community. This JSC-1 distribution did not include detailed recordkeeping to track usage and maintain contact with end users. Thus, while there is an established base of JSC-1 simulant, it is not known what amounts exist or who is in possession of the simulant. Furthermore, the simulant has probably not been stored and utilized as an interlaboratory reference material should be. Communication with a limited group of researchers has indicated that very small quantities of JSC-1 are left in these educational institutions. Characterization of JSC-1 has been limited in scope, due primarily to the fact that this simulant was deployed for engineering testing purposes rather than as a formal SLRS material. Bulk chemistry and mineral compositional data exist but to date have been obtained from limited sampling of the distributed material. Simulant JSC-1 has a composition that is similar to a low-Ti basalt with elevated K and P as is typical for terrestrial basalts, and is a good match to a basalt that has a KREEP component. It also matches the geotechnical properties such as aspect ratio, but exhibits specific gravity data that are lower than lunar materials.

Like MLS-1, JSC-1 thus addresses a specific lunar basalt chemistry and is appropriate for applications that require a specific composition. As will be discussed in the section on root

simulants, the ideal set of root simulants is comprised of a low-Ti mare basalt and a high-Ca highland anorthosite, as these represent compositional end-members that could be physically combined in order to target a spectrum of lunar regolith materials. JSC-1 is of intermediate composition and thus can be used to address this intermediate range of compositions directly, but cannot be used as a simulant for a very low-Ti basalt, for example, as it would require subtraction of a Ti-bearing component. The desirable aspects of JSC-1 are that the source quarry is actively mined and additional material is easily obtained, that distributed material exists in the community, and that the material is relatively well suited for use as a lunar simulant. While JSC-1 contains volcanic glass it is not of a spherical morphology, nor is it like lunar agglutinates. It also does not contain nanophase iron like mature lunar soils. Additionally, any terrestrial material will not have the characteristics of meteorite impact history like lunar rocks and soil exhibit. These characteristics will not be found in terrestrial geological materials due to the absence of extensive meteorite impact events on Earth, and will require modification of terrestrial root simulants to form derivative simulants of higher fidelity, as will be discussed.

4.1.5 Evaluation of Variability of Distributed JSC-1 Simulant in Terms of Size Distribution, Chemistry, and Mineralogy

As this document is being written, a testing program of JSC-1 using distributed stock is underway and an assessment of chemical and physical variability will be evaluated. As it is desirable to utilize a material that has been distributed, this characterization can serve to help calibrate JSC-1 for testing purposes. However, as JSC-1 was not originally produced with quality controls appropriate for a standard reference material, this evaluation is oriented toward assessing the inherent variability of an existing product rather than demonstrating adherence to quality standards that will be implemented in the future.

Preliminary results of geotechnical analysis of JSC-1 stocks from user laboratories indicates that size distribution curves for this material are very consistent. This means that redeployment of JSC-1 simulant can depend on good continuity with previously distributed simulant lots. In this regard, further characterization of existing JSC-1 simulant can be used to bootstrap this material into use as an SLRS material. However, the distributed stocks of JSC-1 are very limited in quantity and this should not be construed as a source of testing material, but rather as a guide in evaluating quality control techniques during simulant production.

4.1.6 Other Lunar Simulants

Lunar simulants have been produced both domestically and internationally. In the United States, a simulant produced by Jensan Scientific, LLC is nominally intended to be a lunar mare basalt simulant. According to the Jensan document sheet, the simulant JS-Lunar Simulant is apparently a physical mixture of "10% aged, brecciated basalt from the Colorado Rockies near Duffey CO, 40% unweathered vesicular basalt from Hawaii, 40% basalt from Pullman WA, and 5% anorthite, purest quality, from the San Gabriel Mountains, CA." The physical mixture of terrestrial basalts is interesting from the root simulant perspective, but the use of material that is of unknown degree of weathering and alteration is problematic. This simulant has not been

developed with the intention of being a chemical and/or mineralogical standard reference, but rather is intended to serve primarily as a geotechnical material.

Lunar simulants have been developed by the Shimizu Corporation in Japan, and are of interest to NASA in terms of application of root simulant models to production strategies. Japanese lunar mare simulants FJS-1, MKS-1, and similar materials have been produced by physically mixing Mount Fuji basalt with olivine and ilmenite mineral separates in order to match a set of Apollo bulk compositions. This matching technique using least squares analysis of modal proportions versus bulk composition will be an important part of the assessment of source materials against targeted soil compositions. Simulants FJS-1 and MKS-1 are comparable to lunar mare simulant JSC-1, but have a higher SiO_2 and lower MgO content, and are representative of material that is more quartz normative than lunar soils, in reflection of the source material used for simulant development.

Simulant development programs have recently begun by the Northern Centre for Advanced Technology Inc. (NORCAT) in Canada, where both basalt and anorthosite simulants are being evaluated. Because these activities are of a proprietary nature, further information is not presented here.

Lunar simulant development has recently begun in China. Lunar mare soil simulant CAS-1 was described by *Zheng et al.* (2005, and personal communication), and derived from volcanic ash of alkaline basaltic composition of Holocene age from Jinlongdingzi (Gold Dragon Peak, in the Jilin Province of Northeast China). This ash has been ground, sized, and placed into storage for use. Simulant CAS-1 is broadly comparable to lunar mare simulant JSC-1, but has a higher Al_2O_3 and lower CaO content, and modally consists of glass, plagioclase, and olivine.

These programs have been instituted outside of the USA due to the difficulties in transporting and obtaining entry of simulant into other countries, balanced against the need for potentially large quantities for testing purposes. There are also issues of proprietary development in the current business environment of space exploration.

Some materials, such as clay and sand, were used during the Apollo program and were specifically implemented for physical testing of mission hardware. It is important to note that their use was intended to provide comparison data and their application to technology development is questionable for future mission planning. These materials were useful to simulate specific geotechnical properties of packed lunar soils. However, lunar regolith contains neither clay nor sand. These materials should not be used as SLRS materials because they introduce physical and chemical properties that do not exist on the Moon.

4.2   Present Status of Lunar Simulant Materials

The availability of lunar simulants is problematic. There are, at present, no root simulants that represent either a low-Ti mare basalt or a high-Ca highland anorthosite. There are no supplies of MLS-1 and JSC-1 available for distribution to the space exploration community to support upcoming mission programs, as the produced materials have been exhausted. While simulant JSC-1 has been distributed to a variety of users, the amounts and documented variability of this

material is unknown and therefore the simulant cannot be considered a standard reference material. To date no simulant has been developed using the necessary procedures and quality control programs that have been used to develop chemical bulk reference materials such as those produced by the USGS and the National Institute of Standards and Technology (NIST). Thus, no current means exist to perform testing using interlaboratory standard reference materials with documented properties, and there is a critical need for SLRS materials that are necessary to perform scientific and engineering tests for process development and flight hardware certification. The lack of a highland simulant currently precludes any serious attempt to model the anticipated mixture of mare and highlands soil types that are expected for landing sites on the Moon that include the lunar polar regions.

The following paragraphs represent a consensus on the findings of the 2005 Workshop concerning the approach to develop SLRS materials for lunar regolith.

4.3   Terrestrial Simulant Materials as Analogs of Lunar Regolith

Terrestrial materials are used to generate lunar regolith simulants, so that appropriate rock and mineral sources on Earth must be identified that exhibit a good match to the bulk chemistry and mineralogy of targeted lunar soils. These materials can then be further processed in order to duplicate the grain size distribution of the lunar material. The concepts of root and derivative simulants are defined and discussed in Section 5.0, Recommendation 1: Standard Lunar Regolith Simulant Materials.

In this workshop, two main root simulants have been proposed, a mare basaltic simulant and an anorthositic highland simulant. The mare basalt root simulant should be a low-Ti terrestrial basalt so that derivative simulants can be formed by addition of a Ti component such as ilmenite. The highland anorthosite root simulant should be a high-Ca terrestrial anorthosite in order to best match the high Ca and Al contents of lunar anorthosites. These details are also discussed in Section 5.0, Recommendation 1: Standard Lunar Regolith Simulant Materials.

Terrestrial rock and mineral source materials can be evaluated against the requirements from the workshop that are based on both activities as well as anticipated landing sites. Matching criteria have in the past been based primarily on bulk chemical composition and grain size distribution, but it is clearly important to address mineral composition as well as textural features and other geotechnical data. Bulk chemistry, mineral chemistry, and textural features are essentially inherent to the terrestrial source material, whereas the grain size distribution is a physical modification that has been superimposed on these other properties in order to target a lunar regolith. Because the chemistry, mineralogy, and textural features are properties of the source material, these terrestrial sources must be chosen with care as these properties cannot be modified in the implementation of a root simulant, and at best can be adjusted in a derivative simulant.

From this line of reasoning it should be evident that several types of simulants can be used to target lunar regolith materials for testing purposes. Root simulants conceptually represent the compositional limits of lunar materials and could thus be physically mixed in order to produce an intermediate composition. A mare basalt and highland anorthosite simulant represent these

compositional limits. On the other hand, intermediate materials like JSC-1 and MLS-1 provide good matches to specific ranges of lunar materials as sampled by the Apollo missions.

Terrestrial source materials that should be evaluated for possible use as lunar simulants include basaltic and anorthositic rocks as well as component minerals such as olivine and ilmenite. While it is desirable to utilize materials that match the mineralogy, materials that are compositional matches could be used to generate synthetic glasses for the purpose of adding an agglutinate component to a simulant.

4.4 SLRS Materials and the Problem of Variability in Natural Soils

An ideal standardized reference material has several requirements. The reference material is typically homogeneous on the scale of the material that is supplied to the end user (i.e., a can or bottle containing the reference material), so that subsequent samples taken from the container are identical within sampling statistics for the material. The reference material should also be homogeneous in terms of the total mass of material, so that a progressive change in characteristics is not observed from container to container in the chronological production run. The reference should be available in sufficient supply to serve the needs of users and to anticipate needs in the future. The reference material should also be relatively inexpensive so that the wider body of the research and engineering community may have access to it for technology development and testing.

Many reference materials exhibit a compromise in one or more of these requirements, and it is homogeneity that is of concern since it is of paramount importance for reference use. SLRS materials are composed of natural rock and mineral materials. Standard reference materials that have been developed for use in the geosciences utilize rock powders that have been ground to a sufficiently fine grain size such that small sample aliquots removed from the distributed material are representative of the larger sample. This is evaluated by comparing major, minor, and trace element analytical data of progressively smaller sample sizes with replicate analyses performed on material drawn from large homogeneous samples. The reduction in grain size effectively eliminates variability as long as the sample size is large enough to represent an average of the compositionally different mineral grains in the powder.

The main problem in producing a lunar regolith simulant is that the grain size variation, from submicron to several millimeters in size, must be retained as a fundamental part of the simulant characteristic. A soil is inherently inhomogeneous in terms of the grain size and mineralogy. To date, there are no systematic studies of the variability in properties of simulant materials as determined by replicate sampling of material. Natural soils have a grain size distribution and also a variable modal abundance of mineral phases in these different size fractions. Experience has shown that as the sample size is reduced, the effect of grain heterogeneity becomes important, and the difference in chemistry between grains dominates the chemical analysis. This variation is reduced or eliminated in standard reference materials by grinding the material to a fine grain size. Since SLRS materials must match the wide grain size distribution of lunar regolith, the implication is that at some reduced sample size, a potentially significant variation in properties will be observed.

This problem is well illustrated by chemical data from simulant MLS-1. As the sample size is reduced, one expects the chemical contrast between grains to become more important, and in the limiting case of sampling down to individual grains, each grain has a completely different composition. There is a minimum sample size that must be determined for each material due to the inherent inhomogeneity in terms of grain size, chemistry, and mineralogy. The minimum sampling size for modern instrumental techniques has trended toward micro-sampling. The data shown for MLS-1 in Tables 4.3A and 4.3B are from Inductively Coupled Plasma (ICP) analysis which requires a milligram sample aliquot. The minimum statistical sample of an inhomogeneous soil is significantly larger than this milligram mass; it is this minimum sample size that must be identified for SLRS materials and recommended to users of the simulants.

Tables 4.3A and 4.3B show the effect of sample size when selecting a small amount of material from a container of MLS-1. Listed in these tables are the average analytical data for replicate sampling of MLS-1 simulant, with the range and deviation relative to the accepted compositional data for MLS-1 (the minimum and maximum values here are not coupled as the original data are not available in the reference). These bulk chemical data are based on an unknown number of samples, but the range in concentrations and analytical total are very large. Note that the variation in SiO_2 is relatively small, approximately 10%, as the modal variation represents changes in phases that have similar SiO_2 content. There is a relatively small variation for SiO_2 because there is little chemical contrast in the mineralogical variation, and Si is a major element in the material.

Conversely, the variation in Cr, a trace constituent, is large, approximately 160%, and reflects the likely inhomogeneous distribution of chromite ($FeCr_2O_4$) in the fines of the soil. In this case the variation in Cr is due to discrete variations in chromite at finer grain sizes, and the large difference in Cr content between chromite and other mineral grains that contain a smaller concentration. Although most silicate minerals contain a small amount of Cr, chromite contains a major amount of Cr and there is a large chemical contrast in Cr content on a grain to grain basis in the simulant. Therefore, a small change in the mode of chromite therefore has a dramatic effect on the bulk chemistry. Thus, it is the chemical contrast that is important when sampling these materials, and one must take care to use a sample size for experiments or testing that appropriately is representative of the larger body of material. An analogous example can be made for geotechnical properties if one considers the effect of a rogue grain of quartz in the soil, so that a large difference in hardness is observed from grain to grain. These rogue grains would dominate the hardness behavior if testing a small quantity of material.

It should be emphasized that when there is either a physical contrast, such as mineral hardness, or a chemical contrast, such as the case for Cr in chromite, reduced sample sizes will result in material that is not representative of the larger bulk mass.

The implication for users is that if, for example, a Cr extraction process was being evaluated, the improper selection of simulant would result in dramatic changes in the test results not due to the efficiency of the process, but rather to the inherent variability of the simulant. It is therefore important to establish sampling requirements for simulant use, and for users to understand the implications of drawing a sample that is too small for the sensitivity of the test being performed.

Table 4.3A Major Element Data for MLS-1 (Values in Oxide Weight Percent, Replicate Analyses)

Oxide	MLS-1	Minimum	Maximum	Range rel to Accepted, %
SiO_2	43.86	41.7	45.90	9.6
TiO_2	6.32	4.82	7.43	41.4
Al_2O_3	13.68	11.76	15.60	28.0
Fe_2O_3	2.60	0.90	4.10	123.1
FeO	13.40	12.00	14.40	17.9
MnO	0.198	0.182	0.218	18.0
MgO	6.68	5.57	8.44	42.8
CaO	10.13	9.04	11.48	24.2
Na_2O	2.12	1.97	2.27	14.3
K_2O	0.281	0.17	0.35	64.6
P_2O_5	0.20	0.02	0.45	215
Total	99.47	88.13	110.64	22.6

Note: Major and trace element data from *Tucker and Setzer*, 1991.

Table 4.3B Trace Element Data for MLS-1 (Values in Parts per Million, Replicate Analyses)

Element	MLS-1 ppm	Minimum ppm	Maximum ppm	Range rel to Average, %
Th	14	13	15	14%
Sr	212	173	253	38%
Co	64	53	84	48%
Ba	95	62	117	58%
V	761	506	952	59%
Cu	445	214	706	111%
Ni	97	53	163	113%
Cr	173	89	366	160%
Zr	47	19	113	200%
Rb	4	1	10	225%

Note: Range is relative to average of MLS-1 data from referenced study, as no published trace element data exist for MLS-1.

The needs of the scientific and engineering communities are to develop and establish a set of SLRS materials that, while retaining the variation in grain size and other properties necessary to accurately represent the regolith, achieve this representation in a reproducible fashion. Thus, the competing needs are to produce SLRS materials that are not inherently homogenous, and to produce it and use it in a way that provides for quality control and reliance on homogeneity at some sample size.

In the development of simulant materials, it is necessary to identify geological materials that are consistently homogeneous at the quarry site, and to process the material, subdivide it, and package it in the form for end-users so that a minimum of variability enters into the production.

Standardization of simulants must be established for physical, chemical, and mineralogical properties. Variability of grain size or mineral hardness within a material is undesirable as inconsistent geotechnical characteristics. Variability of bulk chemical and mineralogical composition is related because the bulk chemistry is a measure of the sum of mineral compositions and their modal abundance in the soil. Thus, standardization and the minimization of variability of SLRS materials will require quality control of the following: the source materials used to generate the simulant, the processing operation necessary to produce the root simulant properties, the blending and homogenizing prior to packaging, and aspects of packaging, storage, and transportation that may, for example, result in segregation of different grain sizes due to mechanical agitation.

4.5   Implications for Development of Lunar Mare Basalt Simulants

The diversity of lunar mare basalt chemistry and mineralogy presents challenges for the development of mare basalt simulants. The extent to which the chemistry and mineralogy are critically important for the diverse set of activities that comprise lunar exploration is currently not known. The division of activities into physical versus chemical in scope has been used in the 2005 Workshop in order to define simulant properties that depend to a lesser and to a greater extent, respectively, on the chemistry and mineralogy of the simulant material. For example, excavating, drilling, and other physical activities are not thought to be affected by chemistry, but the mineralogy affects physical properties (such as mineral hardness) that impact the behavior of the simulant for those activities. Chemical activities such as volatile extraction clearly depend on both the chemistry and mineralogy of the simulant so that processing technologies can anticipate the details of lunar regolith by using a simulant that has high fidelity. Thus, the basic inventory of lunar activities does not permit absolute distinction between physical versus chemical dependency on simulant materials. As a result, it is prudent to use simulants that have relatively high fidelity compared to lunar samples in order to properly anticipate the source materials for these activities.

Simulants that address the range of Ti content in mare basalts were discussed in the workshop and the development of root mare simulants that target both a very low-Ti basalt and a high-Ti basalt can be developed by addition of ilmenite to a low-Ti basalt root. Terrestrial basalts contain oxide minerals representing more oxidizing conditions, such as titanomagnetite, whereas lunar basalts contain ferrous ilmenite and other oxides that represent more reducing conditions. For this reason, it is not possible to duplicate the oxide mineral species in a lunar basalt simulant unless a synthetic material is developed. Lunar basalts also exhibit a diverse set of crystallization and impact modified textures that terrestrial basalts do not generally possess. Lunar basalts have higher liquidus temperatures and lower melt viscosities than terrestrial basalts, and thus have different processing behavior. The petrology and crystallization history of lunar basalts is well studied using programmed crystallization experiments, so much is known concerning the material properties of lunar basalts. There are, however, challenges with regard

to simulating lunar basalts due to differences in texture, bulk chemistry, material behavior, the identity of mineral species, and mineral chemistry as compared to terrestrial source basalts.

An alternative to using simulant materials is to rely on computational methods. The lunar sample inventory can be viewed as variable modal abundances of the opaque minerals and pyroxene, olivine, and plagioclase, as illustrated in Table 3.2. Simply put, a simulant can be viewed as a mixture of minerals that should have the proportions equal to those of lunar regolith samples. This modal abundance coupled with the mineral chemistry can be used to calculate the bulk chemistry of the equivalent rock. Conversely, the bulk chemistry can be processed using a geological normative analysis that yields the mineralogy expected for equilibrium crystallization under a standardized set of conditions. This normative approach to comparing rock chemistry is an important tool for placing materials from diverse environments and planetary bodies into a common basis. The MELTS thermodynamic database (*Ghiorso and Sack*, 1994) can also be used to calculate liquidus relations for the range of expected lunar materials to be used for chemical extraction processes, instead of performing experimental studies using simulant materials. Preliminary results show relatively poor duplication of experimental petrology data from lunar crystallization experiments by these computational methods, though the database includes both terrestrial and lunar calibration data and improvements would be expected using only lunar data. However, this does underscore the need to use simulants with relatively high fidelity, and it is anticipated that computational methods will supplement experimental data and can be used to aid in the identification of inconsistent experimental or test results.

4.6 Implications for Development of Lunar Highlands Simulants

The dominant highland rock type is anorthositic in composition, so that a highland lunar simulant must approximate the characteristics of a plagioclase-rich rock which also satisfies the minor mineralogy and chemistry as detailed in the Lunar Sourcebook. To a first approximation, the lunar anorthosites can be considered plagioclase rocks with small modal abundances of olivine and pyroxene with traces of other mineral components (see Figure 4.5). In that regard, they are chemically and mineralogically less complex than the mare basalts, though they have significant textural variations due to their long impact histories. The limited sampling from the Apollo missions does not shed light on the areal distribution of anorthositic breccias, so any variation in the size and shape of rock fragments with distance from a crater or other topographic feature is unknown. These variations will need to be anticipated for lunar processing operations.

Anorthosite bodies on Earth are ancient like those on the Moon, and therefore tend to have a metamorphic overprint including hydrous alteration that is undesirable for use as lunar simulant materials. Terrestrial anorthosites tend to have lower bulk Ca content, as well as a less Ca-rich anorthite content of the plagioclase, as they have formed from source materials that are different from those on the Moon. However, anorthosite materials from the Stillwater Intrusion in Montana, and from the Duluth Complex in Minnesota, are both good candidates for use as an anorthosite-based lunar highland simulant due to minimal hydrous alteration and comparatively high Ca-content of the plagioclase. These terrestrial anorthosite bodies have not been subjected to meteorite bombardment histories and so do not have textures like their lunar counterpart. The selection of geological source localities for use in simulant production is discussed further in Section 5.0, Recommendation 1: Standard Lunar Regolith Simulant Materials.
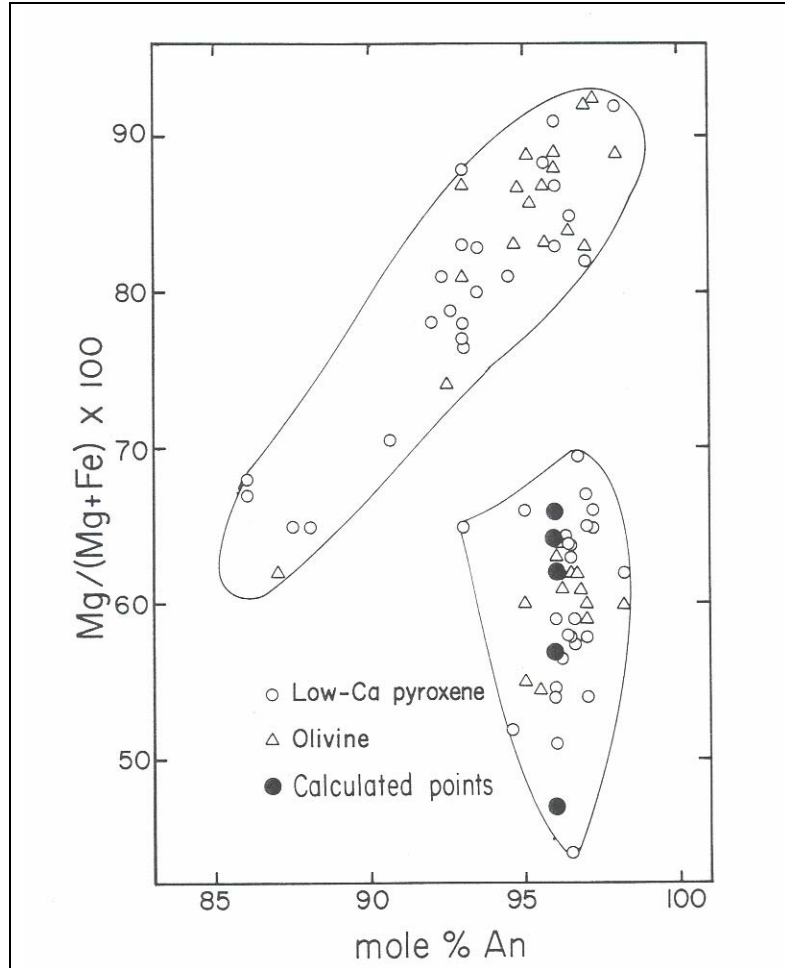
Figure 4.5 Compositional Variation of Pristine Lunar Highland Samples. Plot of mole % An in plagioclase versus mole % Mg/(Mg+Fe) in coexisting mafic minerals for pristine lunar highlands samples. Calculated points represent a selection of ultimate plagioclase and orthopyroxene compositions for lunar highlands data (*Raedeke et al. 1980*). This plot illustrates the existence of two distinct groups of primitive lunar crustal rocks that still challenges petrologists; the "vertical" trend is defined by anorthosites, noritic anorthosites, and troctolite anorthosites of the ferroan anorthosite suite from Apollo 15 and 16. The oblique trend is defined by rocks relatively richer in mafic phases, mainly norites and troctolites from Apollo 15 and 17.

4.7 Pitfalls in the Selection and Use of Simulant Materials

Lunar simulants JSC-1 and MLS-1 have been developed as basaltic mare simulants. The positive and negative aspects of these simulants have been previously discussed in terms of the degree of match, or simulant fidelity, compared to targeted lunar regolith materials. This fidelity has been evaluated relative to the bulk chemistry, mineralogy, and grain size distribution of these simulants. These two simulants are relatively good choices for study of processes that are anticipated to be used in lunar mare environments, but may not be appropriate for evaluation of processes anticipated for the lunar highland environment, where an anorthositic composition is dominant.

One goal of this report is to communicate the need to use appropriate SLRS materials for research, development, and testing by the science and engineering communities. However, as the following discussion emphasizes, poor choice of testing materials are apparently being made in the testing community with regard to simulant use. Discussion with individuals that are not familiar with simulant issues has revealed a relatively poor recognition of the importance of

matching the bulk chemistry and mineralogy of simulants or test materials to intended applications. In some cases, inappropriate materials such as concrete dry mix have been used for testing. While concrete does contain Ca-rich silicate phases, the mineralogy differs from both terrestrial and lunar basalts and anorthosites, and the cement-forming behavior of dry mix in the presence of water is obviously not comparable to lunar regolith. This problem highlights two issues. First, there is a need for education concerning simulant use and misuse. One should not be surprised at the lack of interlaboratory comparability when inappropriate testing materials are used. Indeed, there is no interlaboratory comparability when it is left to individual choice to select simulant materials for testing. Secondly, if SLRS materials were widely available, individuals would not resort to commonly available but inappropriate testing materials. Thus, a well implemented simulant program addresses both educational and scientific goals by using proper materials and avoiding mistakes.

It is instructive to demonstrate the pitfalls of inappropriate choice of simulant materials with an example. The extraction of volatiles and metals from lunar soil forms the basis for ISRU activities upon which a host of technologies may depend. In particular, the in situ production of purified silicon metal is desired to enable the fabrication of photovoltaic solar cells. Segregation of silicon results from chemical reduction of silicates in soil that has been melted. In the idealized case, spherical silicon grains are produced in the melt and are separated by either sinking or floating, depending on the relative density of the silicon compared to the melt. If a given lunar soil is melted, then allowed to slowly cool, either olivine or plagioclase crystallizes first, followed by other phases depending on the soil chemistry. The density of a crystal-melt mixture is a function of temperature, bulk chemistry, mineralogy, and the proportions of crystals and melt.

Calculations have been made for three terrestrial rock compositions that represent conceivable choices for simulant use. These are lunar mare simulant JSC-1, geochemical basalt reference BCR-1 which is broadly similar in composition to JSC-1, and geochemical reference RGM-1 which is a rhyolite (i.e., granite). Melt densities for these three compositions have been calculated using the program PELE (*Boudreau*, 1999), which uses the core algorithms of the thermodynamically valid MELTS software, and provides crystal-melt equilibria, density, and melt viscosity data as a function of temperature during calculated melting or crystallization runs. Melt density data were used to calculate Stokes-law settling rates for 1 mm grains of silicon metal for the three materials. As Figure 4.6 illustrates, the choice of source material composition is critical to the correct analysis of silicon grain segregation. As silicon is less dense than the coexisting melt for lunar simulant JSC-1, grains should float in a melt of this basaltic composition. Note that the degree of floating is diminished for the case of basalt BCR-1 where neutral buoyancy is indicated for typical processing temperatures. Silicon has a higher density than a coexisting rhyolite melt and is predicted to sink according to these calculations. With reference to Figure 4.7, each of these material compositions exhibits viscosity-temperature relationships that have differing slopes and changes in slope as different minerals begin to crystallize. Thus, the density and viscosity behavior of these three materials are different enough to be of concern when designing experiments for lunar processing.

These results, while simplified, clearly demonstrate the use of an inappropriate simulant material, even basalt BCR-1 that is similar in chemistry to JSC-1, may produce erroneous

processing data. In the worst case, a chemical processor designed to produce purified silicon might be equipped with instrumentation that was developed using a simulant that predicted grain settling, when the opposite would be observed as lunar soil was processed for the first time on the Moon.

The use of appropriate SLRS materials to simulate lunar regolith thus reduces technology and mission risks, and the use of inappropriate simulants virtually ensures increased risk.
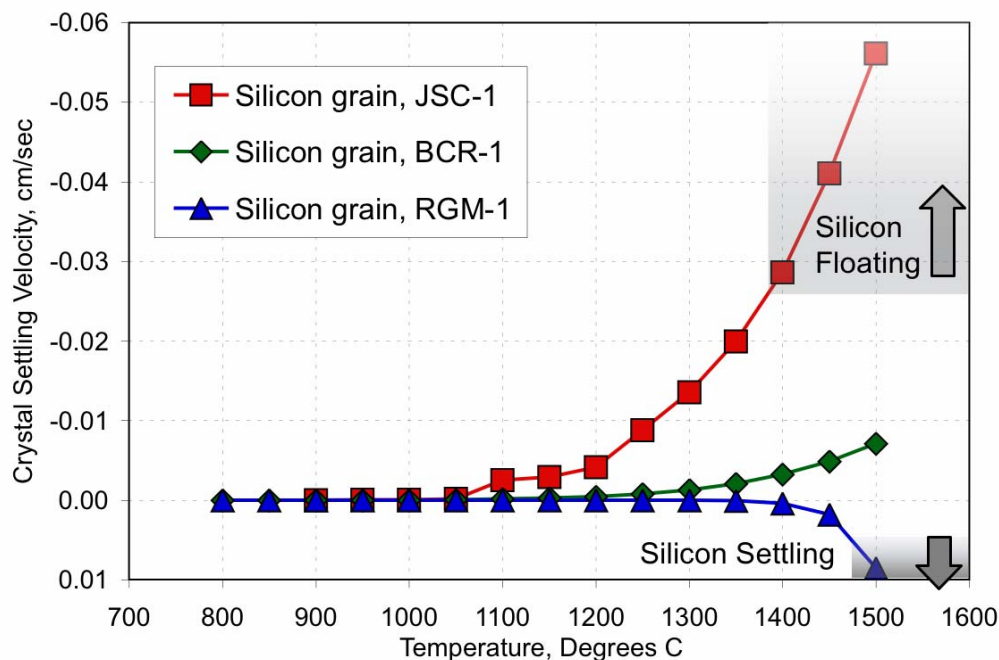
Figure 4.6 Predicted Settling Behavior of Silicon Grains in Melts of Compositionally Different Materials. This figure illustrates how the choice of lunar regolith simulant among candidate materials will impact the design of a chemical processor for silicon extraction. Data plotted for lunar mare basalt simulant JSC-1, USGS basalt BCR-1, and USGS rhyolite RGM-1.
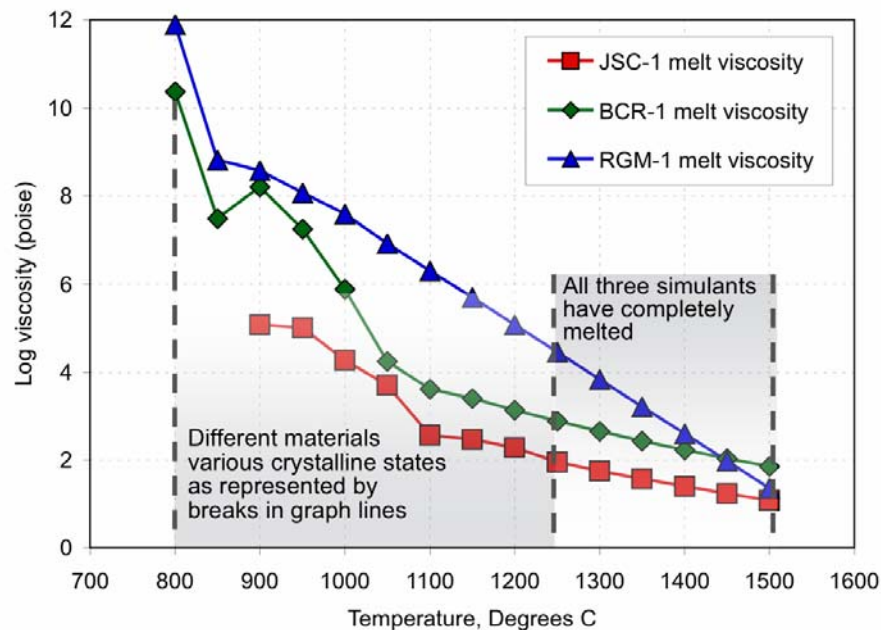
Figure 4.7 Calculated Melt Viscosity Data for Compositionally Different Materials.   The different viscosities of candidate simulant materials impact the engineering of chemical processors in ISRU by changing the requirements on input power and operating temperatures for the removal of products. Data plotted for lunar mare basalt simulant JSC-1, USGS basalt BCR-1, and USGS rhyolite RGM-1.

4.7.1 Oxidation State of Fe and Oxygen Fugacity Control

In addition to proper selection of simulant materials, it is also critical to duplicate the lunar surface conditions in experiments and test environments where it is important to do so. The lunar surface is characterized by a hard vacuum, and lunar materials have equilibrated under reducing conditions on the Moon. These conditions are quantitatively described by oxygen fugacity buffer assemblages, which define a curve on a plot of oxygen fugacity versus temperature. In general, lunar materials have equilibrated at the more reducing iron-wustite (Fe-FeO) buffer, whereas terrestrial igneous rocks have equilibrated at the more oxidizing fayalite-magnetite-quartz (Fe_2SiO_4-Fe_3O_4-SiO_2) buffer. High temperature processing experiments using lunar simulant materials that aim to duplicate conditions on the lunar surface require experimental control of vacuum and oxygen fugacity to the appropriate values.

Researchers not familiar with experiments involving Fe in multiple oxidation states must address this fugacity control if proper calibration is to be made compared to the lunar environment. Furnace processing in open air on Earth typically results in fully oxidized iron as Fe^{3+} due to equilibration above the Fe_3O_4-Fe_2O_3 buffer. Thus, the use of experimental apparatus in open air will result in significantly higher oxygen fugacity compared to the desired lunar conditions. We have observed this error on several occasions by workers new to the field of lunar and martian processing, who have attempted to incorporate magnetic processing with furnace melting studies;

the magnetic behavior of metallic Fe, FeO, Fe_3O_4, and Fe_2O_3 differ markedly and warrant attention to fugacity control during processing. Furthermore, the identification of the oxidation state of Fe species cannot be obtained in general from x-ray diffraction (XRD) or x-ray fluorescence (XRF) methods.

The definitive determination of the oxidation state of Fe is accomplished using Mössbauer spectroscopy, where the measured spectra indicate the valence in the phases examined. This measurement capability can be added to high temperature experimental apparatus.

4.8   Specific Differences (Agglutinates, Nanophase Iron, Shocked Grains, Solar Wind Implantation, H_2O-Free)

Several features of the lunar regolith will be important components of simulants that achieve a high fidelity match. These features include glassy agglutinates, Fe nanophase particles, mineral grains that exhibit shocked textures, and solar wind implanted grains. These characteristics are not present in terrestrial materials since solar particles and meteorite bombardment is not an active process on Earth and ancient soils that were modified by such processes have been weathered or recycled. However, each of these features can be duplicated in small quantities for high fidelity simulant material.

4.9   Production of Glass and Agglutinates

The production of glass fragments from lunar simulant MLS-1 was attempted using a plasma torch to melt simulant feedstock as it entered an evacuated column, resulting in the formation of molten spherical droplets during free fall. Plasma melting was shown to be a viable method for producing simulants of some glassy components of the lunar soil *(Weiblen et al.,* 1990) but failed to produce analogs of lunar agglutinates. The technique has been evaluated using an in-flight sustained shockwave plasma (ISSP) reactor at the Mineral Resources Research Center at the University of Minnesota (Figure 4.8). The 10-m-tall reactor consists of a cylindrical stainless steel arc chamber lined with refractory material mounted above additional refractory-lined sections that provide a free-fall zone and collector at the bottom. The arc chamber consists of a vertical, hollow, water-cooled graphite cathode that is radially surrounded by the arc plasma gas (argon or nitrogen). Sample materials are fed through the hollow cathode. Arc rotation, produced by utilizing the principle of a direct current (DC) motor, maintains the shockwave plasma in a rotating, homogeneous magnetic field in the plane of the anodes. Rotational speeds have been measured in the range of 1000 to 3000 rpm, depending on the operating conditions *(Reid et al.,* 1987). This reactor was operated at 400 A and 150 to 250 V to test the effect of the plasma processing on a basalt feedstock. Run products with 10 to 30% glassy material were achieved with feed rates of 40 to 50 kg/hr. To date, argon has been the plasma gas and no control of the oxidation state of the atmosphere in the plasma has been made in the system. Run products consisted of unreacted mineral fragments, massive, globular glass, and vesicular glass in a variety of textures that resemble some of the glassy components of lunar soils (Figure 4.9). The glass also contains immiscible native iron blebs. However, iron-titanium oxide phases, probably with some ferric iron, also occur in the glass and it is not clear if single-domain iron is present. The proportions of these components depended on the power, grain size, and rate of

grain feed through the hollow cathode. The principal chemical difference between the feed and the run products under these conditions has been the reduction of the water content of the glass by an order of magnitude to 0.06 wt%. Further refinements of this plasma process should be considered for experimental trials in an attempt to more closely simulate the chemical, mineralogical, and textural features of lunar soils.

Nanophase iron can be produced but must be stabilized against reaction with water vapor or oxidation to ferrous or ferric oxides. Terrestrial materials also typically contain some amount of water, and the anhydrous nature of lunar materials will require that simulants contain a minimum of minerals that have structural water.

It is also important to consider terrestrial elements or minerals that would represent contaminants to the processes being studied for implementation on the Moon. For example, the presence of quartz (a very hard mineral) is undesirable in an SLRS material from a geotechnical perspective, as quartz is rare in the lunar regolith but relatively common in terrestrial materials.
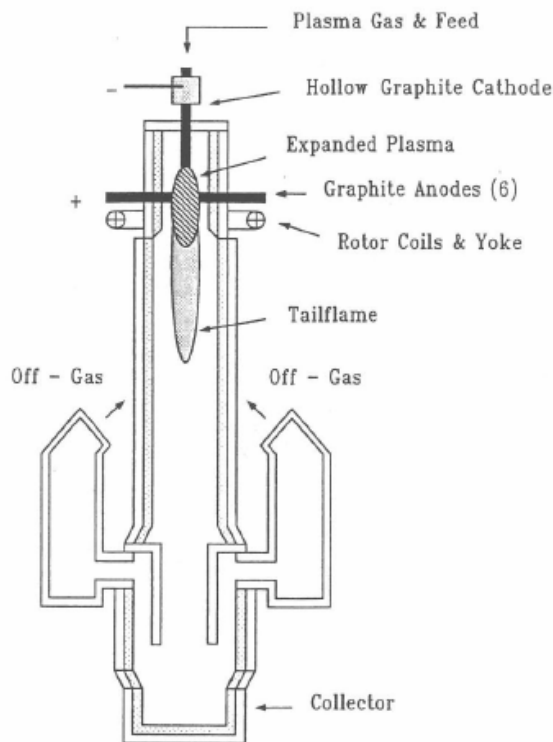
Figure 4.8 Schematic of In-Flight Sustained Shockwave Plasma Reactor
(ISSP) Used to Produce Synthetic Agglutinates
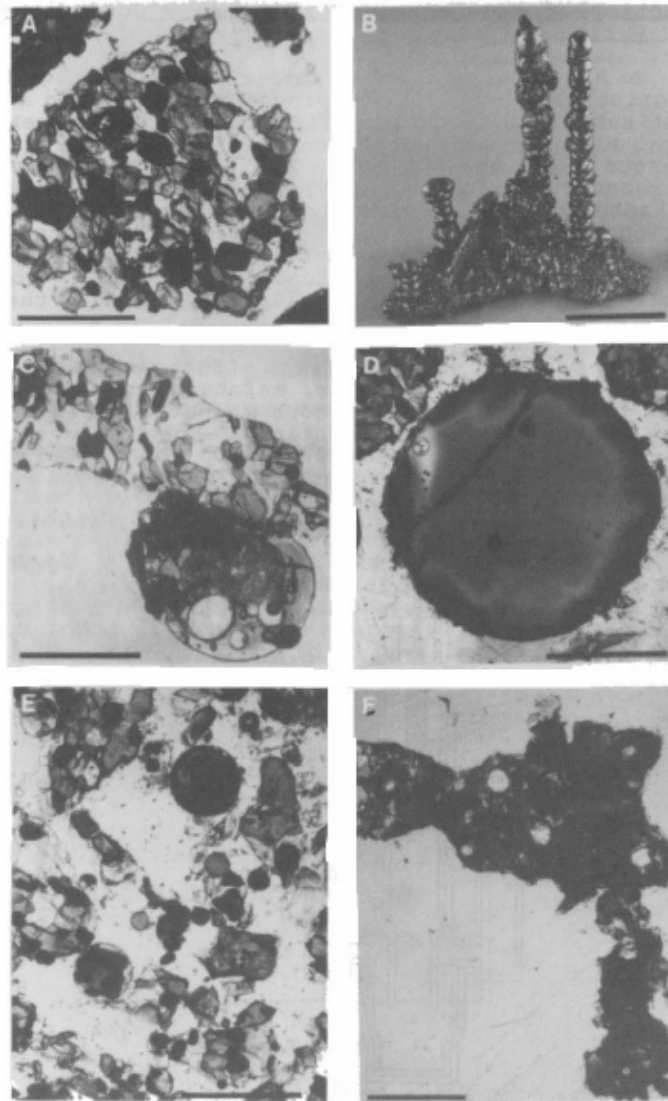
Figure 4.9 Photomicrographs of Materials from ISSP Runs. Scale Bar: A and C-F
(0.5 mm), B (2.5 cm).

A. Unreacted Rock Fragment

B. Globular Glass Quenched in the Reactor Collector.

C. Vesicular Glass Sphere Welded To Unreacted Rock Fragment.

D. Glass Sphere.

E. Less Than 0.5 mm Size Fraction of Run Products. The proportions of glass spheres increases as the size fraction decreases.

F. Complex Mass of Rock Fragments and Vesicular Glass that Resembles Lunar Soil Agglutinates. (*Alton et al*. 1985).

4.10 Lunar Dust

The topic of lunar dust has been of central importance from a scientific as well as operational perspective. The electrostatic charging behavior of lunar dust must be addressed for simulants as this is an important property of the lunar regolith. The effect of lunar dust adhesion in terms of material abrasion and contamination issues is also important. Experience with the LRV has demonstrated that dust was a significant problem. Dust was lifted by the wheels and deposited on portions of the vehicle and the astronauts. A particular problem was the accumulation of dust on the cooling radiator assemblies which required the astronauts to stop and attempt to remove the dust; this activity was ultimately never successful (see Figure 4.10 and Figure 4.11).

Anecdotal experiences of the Apollo astronauts illustrate well the problems of toxicology and contamination of the living quarters by dust. Dust penetrated the joints of the space suits and caused significant damage; additionally, dust in the suit seals resulted in significant degradation in their ability to maintain pressure (*Gaier*, 2005).

The reproduction of several key properties of the dust fraction of the lunar regolith is a high priority in the development of SLRS materials. Although a thorough examination of the lunar samples below 20 μm is still needed to categorize particles by physical and mineralogical types, several key characteristics are known and must be reproduced. Our present knowledge indicates that these particles are comprised of glass and agglutinate fragments, glass microspheres, and mineral fragments and contain nanophase Fe (Figure 2.5). The angular shape of these fragments is a critical property that dictates their surface reactivity, including their surface charging properties and their adhesive properties. The characteristics of the dust grain surfaces at the molecular level while in the lunar environment are not entirely known at this time. Nevertheless, the highly reducing vacuum environment coupled with episodic impacts that fracture the grains is conducive to the generation of exposed unsatisfied bonds that dictate surface interactions between dust particles, hardware surfaces, and crew. The understanding and simulation of these properties is a research area of high importance to enable scientists, engineers and mission planners to properly evaluate the risks posed by lunar dust to a long-term presence on the Moon.
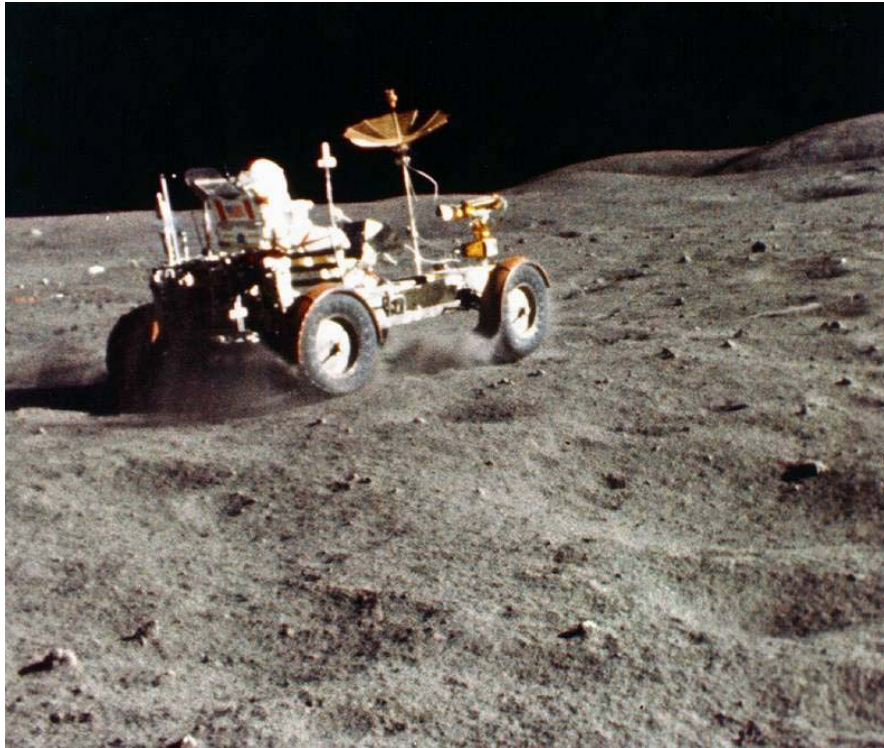
Figure 4.10 The LRV During Locomotion. Lunar dust was frequently lifted by the wheels and deposited over the LRV. Apollo 16 Photograph AP16-S72-37002
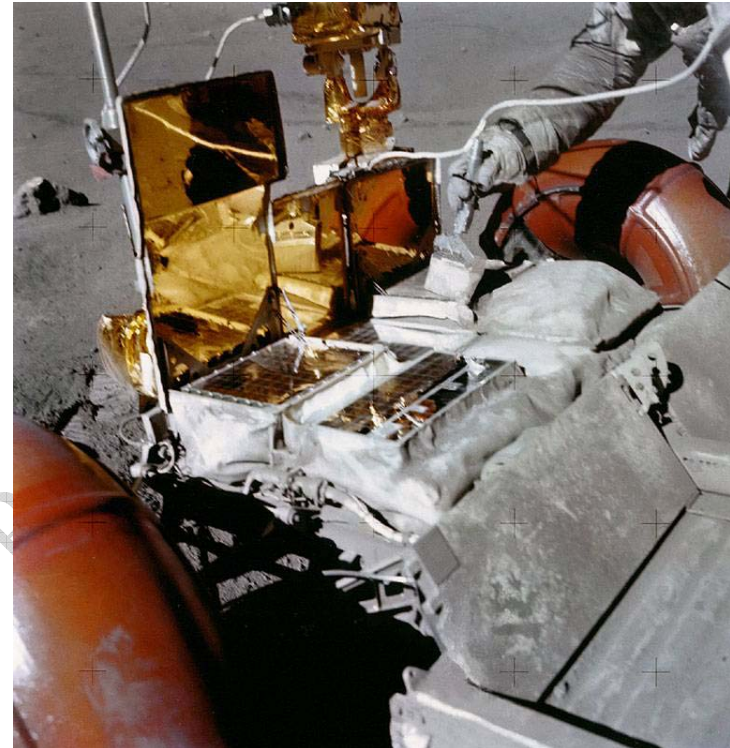
Figure 4.11 LRV Dust Buildup. This close up of the LRV shows Astronaut Charles Duke brushing dust from the battery radiator. Apollo 16 photograph AS16-116-18717

4.11   Summary of Lunar Regolith Evolution in Relation to Simulant Development

The lunar regolith is a complex assemblage of rock, mineral, glass, and metal particles. As previously discussed, the geological history of the Moon can be described as an early melting event that caused plagioclase to float, forming the lunar highlands, and later impact events that formed the circular mare basins that were later filled by large flood basalts. These two basic rock types were extensively modified by meteorite impact events, which caused local mixing of mare and highland material in the lunar regolith. These impact events produced a diverse array of textures and overprinted chemical and mineralogical changes in the regolith. These impacts also caused localized melting and evaporation, and it is generally recognized that the maturity of the lunar regolith can be measured from the proportion of nanophase iron particles that are found in a given regolith sample (Figure 2.5). As the number of impacts increases, the concentration of nanophase Fe increases in small grains due to melting, evaporation, and condensation in the lunar vacuum where reducing conditions transform oxidized Fe into metallic Fe. Melting of fine particle sizes and welding of these molten droplets has formed the agglutinate fraction of lunar soils (Figure 2.5). Complex impact processes have produced breakage of rock and mineral grains to form the diverse breccias that are observed in lunar samples (*McKay*, 1991).

This diversity of lunar textures and impact features is not typical of terrestrial rocks. Lunar materials are compositionally more simplified but texturally more complex than terrestrial materials due to the less diverse set of compositional source materials but more diverse impact processes. Terrestrial rocks exhibit a wider range of compositional diversity as well as weathering features that reflect reaction with air and water. The challenge for development of lunar simulants is to find compositionally similar materials to those on the Moon, and to process them in a way to mimic the lunar materials. It is desirable to eliminate or reduce those features such as oxidized iron from terrestrial source materials that are to be used for lunar simulant development.

4.12   Standardization and Traceability of SLRS Materials

Two aspects of the development of SLRS materials are the need to standardize the proposed materials and to provide traceability of the simulant for the purposes of comparison.

Traceability of simulant characterization refers to the calibration of characterization techniques that are used to produce data on the simulant materials, and the chain of calibration back to a master set of reference standards. This includes traceability for geotechnical, chemical, mineralogical, and other characterization methods. Traceability for chemical analysis is established by utilizing a common set of analytical primary reference standards that each characterization facility uses to ensure interlaboratory consistency or continuity between sample batches. For example, during analytical runs, laboratories should use geochemical reference standards such as NIST SRM 688 or USGS BCR-2 material as part of a quality control program for certification of the lunar simulants. Analyses of these reference standards would be run concurrently with simulant material and results reported for use by NASA and the science and engineering communities.

For an end user, traceability of SLRS materials appears in the form of the certificate that documents the placement of the simulant material within the production sequence, and includes all compositional and other information specific to the reference material. Traceability also includes the availability and reliability of database information that summarizes the distribution and use of simulant by the science and engineering community.

In discussions since the workshop, it has become apparent that distribution of JSC-1 simulant took place in an informal manner, with approximately 50% or more of the material distributed to primarily educational institutions. At least one instance of confusion as to the identity of simulant material has occurred, and required chemical analysis of the material in order to identify it as Napa Valley Basalt. The material in question was described as an additional JSC-1 clone, clearly in error. This incident points to another aspect of labeling and traceability needs. Distributed SLRS materials must, by agreement of the end user, be stored in the container that was used for original distribution. The certification applies to the SLRS material as stored in that container, and once removed from the container, the chain of custody has been compromised and issues regarding sampling enter the picture. For reasons like these, NIST certifies and distributes standard reference glasses in disk form so that if inhomogeneity is later identified, the user can appropriately respond for the material they have in their possession. If the standard is crushed or modified, the NIST certificate no longer applies. An approach similar to this is recommended for simulant distribution in order to eliminate errors, and also to minimize modification to the SLRS material due to improper storage.

Discussions among 2005 Workshop attendees supported the ideas presented above. In particular, it was agreed that the community needs widely accepted standardized simulant materials, namely SLRS materials, and that a database for tracking information is important. Traceability of SLRS materials was identified as a critical component of simulant development.

5.0   RECOMMENDATION 1: STANDARD LUNAR REGOLITH SIMULANT MATERIALS

In 2005 Workshop breakout sessions, the expert groups were asked to discuss alternative concepts for the definition of families of SLRS materials and propose their recommendation for a list of simulant materials. In the end, these expert groups recommended the concept of root and derivative simulants that support activities at localities in lunar mare regions, highland regions, and lunar polar regions as described below. These concepts and the formal list are discussed in the following sections.

However, the 2005 Workshop participants recognized the need for immediate availability of a simulant that serves as a general purpose material for simulation of mare basalts. For this reason, a timely redeployment of lunar simulant JSC-1 was endorsed by the group. In response to this recommendation, NASA/MSFC has initiated a production run of material to generate SLRS lunar mare simulant JSC-1A. Delivery of this material is expected by December, 2005.

5.1   Definition of Root Simulant

A *root simulant* is a material that approximates a targeted regolith material, is composed of rock, mineral, or synthetic source materials, and ideally represents an end-member in terms of physical, chemical, and mineralogical properties relative to the targeted regolith. By definition, it inherently approximates the predominant characteristics of the lunar regolith under consideration and does so with a minimum degree of processing. Terrestrial materials are derived from different source materials compared to the Moon, and have been altered and weathered by processes that do not include extensive meteorite bombardment, as is the case for lunar materials. Terrestrial materials that match the bulk chemistry and mineralogy of lunar materials typically must be milled or physically processed to duplicate the grain size distribution of lunar regolith. It should be mentioned in this definition that meteoritic source materials, or any other material that presents an inherently good match to the target, is also of interest; however, the practicality of using meteorites poses the same problems as discussed for lunar samples as they too are very valuable. A root simulant is ideally an end-member in terms of properties, e.g., a low-Ti basalt or an anorthosite nominally free of mare basalt material. These root simulants can in principle be physically mixed in order to match the range of lunar regolith materials that represent differing contributions from mare and highland sources.

The concept of root simulants includes materials that are practical candidates, such as basalts and anorthosites, for their obvious chemical and mineralogical similarity to lunar mare and highland materials, respectively. Ultimately, the development of root simulants depends on the suitability of terrestrial materials of these types. The root simulant concept can be expanded to include any property that must be modeled between end-members that represent the spatial range of material properties of the targeted regolith samples. For example, analysis of these end-members may focus on bulk chemistry (of major, minor, and trace elements), mineralogy, and physical properties such as grain-size distribution or mineral hardness. It is therefore appropriate to apply analytical methods to the selection of root simulant materials by analysis of the targeted regolith samples and extraction of principle components in order to better define the nature of the root simulants.

5.2 Definition of Derivative Simulant

A *derivative simulant* is a simulant that is based on a root simulant and nominally has the root properties, but also has modified properties that more closely match the targeted regolith. It is a material obtained by subjecting a root simulant to a variety of processes such as chemical and/or mineralogical modification (i.e., end-member mixing, glass formation, and nanophase Fe glasses), addition of physical components (i.e., minerals and glass), or physical modification (i.e., ultrafine grinding, fragmented dust particles, and ion implantation).

By varying the mixed proportions of root simulant and additive standard minerals, a range of regolith compositions could be matched. For example, an ideal root simulant is a low-Ti basalt which could be mixed with a second root material containing Ti in order to duplicate the range of Ti content observed in lunar samples. A root simulant that has an intermediate Ti content can, in general, only be used to duplicate compositions that have a greater Ti content by addition of a Ti component such as ilmenite ($FeTiO_3$). Potential additives are terrestrial mineral separates such as olivine, ilmenite, and plagioclase. It is therefore possible to generate a simulant by physically mixing a selected combination of rock powders, mineral separates, and synthetic materials. This procedure has been used in Japan to produce a high-Ti mare basalt simulant by mixing Mt. Fuji basalt (low in Ti and Mg) with ilmenite and olivine, in order to boost those elements in the targeted composition. However, this mixing methodology must be evolved to obtain lithic fragments rather than physically separated mineral components, as the behavior of rock fragments is fundamentally different than mineral grains in these materials.

The production and addition of microspherical glass, agglutinates of glass and mineral fragments, implanted solar-wind molecules, and nanophase Fe particles have been discussed within the framework of a derivative simulant. Microspherical glass could be produced using an evacuated column with a plasma torch and feedstock assembly in order to feed simulant into the plasma flame. A root simulant that contains no glassy component could be used as the feedstock to generate glasses and agglutinates that would in principle have the bulk composition of the root simulant and could be physically mixed back with the root simulant to obtain a derivative simulant with higher fidelity. Ion implantation by irradiation of root simulants could yield an additive component with grain boundary damage features and solar wind implanted species similar to that of the lunar regolith. Nanophase Fe glass is an important component of the lunar regolith especially in small grains; chemical synthesis methods are being considered to obtain reduced iron nanoparticles in glass matrices whose composition approximates the compositions found in lunar samples (*Liu et al.*, 2005).

Derivative simulant processing thus includes chemical and physical processing of root simulant materials. The division between root and derivative simulants is again dictated by the practical aspects of obtaining materials that in raw form are similar to targeted lunar soils, and can be obtained in tonnage quantities, compared to the needs for smaller amounts of simulant that would be utilized for specific applications. For example, it is anticipated that in general, root SLRS materials would serve the community needs for activities that are predominantly physical, such as drilling and excavation, whereas a simulant produced by derivative processing would provide higher fidelity materials for chemical activities such as oxygen extraction.

5.3 Recommended Family of Lunar Simulants

The concept of root and derivative simulants was applied to the need for lunar simulants by the 2005 Workshop. Discussions centered on lunar activities, the ranking of lunar regolith properties based on activity and landing site needs, and the anticipated lunar landing sites for missions. Based on an evaluation of these factors, a fundamental family of recommended SLRS materials was identified by the 2005 Workshop. The following sections outline this family of simulants.

The proposed roots represent chemical and mineralogical rock and soil materials that are appropriate for use as simulants. The identification of terrestrial source areas that can be utilized for these root simulants will require a careful assessment of characteristics of the source materials. This process will require evaluation of geochemical and mineralogical databases that summarize this information. It is anticipated that several candidate localities will be initially selected for further screening prior to a final selection of a locality. A number of databases are currently available for this purpose.

5.3.1 Root Lunar Mare Simulant: Low-Ti Mare Basalt

Lunar mare basalts exhibit a range of Ti content, ranging from low-Ti to high-Ti basalt (see Table 3.1). The most attractive simulant materials are those that match specific lunar regolith compositions and can be modified by addition of components to match a wider range of compositions. The best choice for a root mare basalt simulant is a low-Ti basalt that represents a compositional end-member. A potential candidate for a low-Ti root mare simulant is a terrestrial source material with a composition and mineralogy similar to an Apollo 15 low-Ti basalt. This root simulant can be modified as a derivative simulant by the addition of Ti in the form of ilmenite. This low-Ti mare basalt simulant thus has the greatest flexibility in matching a wide range of mare regolith compositions and properties by adjustment of the Ti component.

A suitable source material for this low-Ti mare basalt simulant is terrestrial basalt that has compositional and physical properties similar to low-Ti lunar mare basalt. In particular, a volcanic ash is attractive because these materials typically contain a glassy component as well as porosity and vesiculation that are similar to textural features of lunar basalts. A terrestrial ilmenite with low Fe^{3+} can be used to add Ti to the root basalt in order to form a set of derivative basalts with the required Ti content. Examples of calculations for mixing of rock and mineral components to target a lunar composition are shown in Tables 5.1 and 5.2 (*Carpenter*, 2005).

Conversely, a less suitable choice for a lunar mare basalt simulant is any material that contains an elevated Ti content, as it is difficult to chemically remove a component from a rock. Simulant JSC-1 contains a Ti content similar to an Apollo 14 basalt, and is suitable for simulation of these compositions, but not for lunar basalts with low-Ti content.

In summary, the best choice for a root simulant of a low-Ti lunar mare basalt composition is a low-Ti terrestrial basalt obtained from a source that contains a glassy component. Derivative

simulants can be formed by addition of component(s) that contain Ti, as well as other components or processing to increase the simulant fidelity.

5.3.2   Root Lunar Highland Simulant: High-Ca Highland Anorthosite

Lunar highland materials are predominantly composed of anorthosite, and have a more restricted range of composition compared to mare basalts. Again, with respect to highland simulants, the most attractive simulant materials are those that match highland anorthosites. The best choice for a root highland simulant is a high-Ca anorthosite that represents a compositional end-member for lunar highland anorthosites. Compared to mare basalts, highland anorthosites show less compositional diversity, but significant textural and physical diversity. For this reason, it will be important to select an appropriate high-Ca anorthosite, but also to address the addition of a glassy component to the anorthosite in order to match the impact-melt glass component of lunar anorthosites.

A suitable source material for this high-Ca highland simulant is a terrestrial anorthosite that has compositional and physical properties similar to a high-Ca lunar highland anorthosite. Examples of calculations for mixing of rock and mineral components to target a lunar composition are shown in Tables 5.1 and 5.2.

Table 5.1 Example of Root Simulant Calculations Using Mineral Roots
to Match Apollo 16 Target

Oxide	Olivine Fo_{92}	Anorthite	Quartz	Root Mix	Apollo 16*	$Diff^2$
SiO_2	41.23	43.19	100	46.29	45.00	1.65
Al_2O_3		36.65		28.59	27.30	1.66
FeO	7.89			1.26	5.10	14.73
MgO	50.89			8.14	5.70	5.97
CaO		20.16		15.72	15.70	0.00
Total	100	100	100	100	(100.78)	
Explanation: Oxide weight percent data for Olivine, Anorthite, and Quartz hypothetical mineral root materials. Root Mix is weight percent of oxide constituent based on proportions of olivine, anorthite, and quartz in physical mixture. For SiO_2 calculation this is Wt% SiO_2 = (% olivine)*41.23 + (% plagioclase)*43.19 + (% quartz)*100 = 46.29. $Diff^2$ is square of difference $(L_i-C_i)^2$ between Root Mix and Apollo 16 target. Sum of differences $(L_i-C_i)^2$ = 24.75, R = sqrt(24.75 / n=14 oxides) = 1.33. This example is for mix of 16% olivine Fo_{92}, 78% Plagioclase An_{100}, 6% quartz. Apollo 16 analysis includes other minor elements not listed here.						

Table 5.2 Example of Root Simulant Calculations Using JSC-1 Simulant and Mineral Roots to Match Apollo 11, 14, and 16 Targets

Root Component	Apollo 11 High Ti			Apollo 14 Low Ti / KREEP		Apollo 16 Highland	
R_{min}	1.68	1.41	1.43	1.51	1.22	1.90	1.88
JSC-1 %	86	61	50	100	71	27	23
Ilmenite %	14	12	15		2		
Olivine %		2	5		4	3	5
Ca-pyroxene		15					
Plagioclase		10	8		10	70	70
Glass			22		13		2

Notes:
Best match is for lowest R_{min} value. Left column for each target represents the simplest mixture, right hand column(s) represent progressively more complicated mixtures that achieve lower R_{min} and better match. Glass and Ca-pyroxene present separation challenge due to grain size in JSC-1 bulk material. Minor phases and trace glass chemistry ignored.
Apollo compositions from, Lunar Sourcebook, Table 7.15, p. 346.

Conversely, a less suitable choice for a lunar highland simulant is an anorthosite that contains a reduced Ca content (as this will also reflect a higher Na content due to plagioclase feldspar chemistry), as it is difficult to chemically remove Na and add Ca components. Because anorthosites are intrusive igneous rocks, they have cooled slowly and do not contain a glassy phase. Lunar anorthosites have been partially melted by impact events and are characterized by a significant glassy fraction. A lunar highland simulant needs to address this deficiency in terrestrial anorthosites.

During the 2005 Workshop, discussion took place concerning the difference in anorthosite composition concerning Mg-rich and ferroan anorthosites. These compositional differences and also possible differences in highland composition for the lunar far side compared to the lunar near side were brought up. These differences were not thought to present significant issues for current simulant development plans.

In summary, the best choice for a root SLRS material of a high-Ca lunar highland anorthosite composition is a high-Ca terrestrial anorthosite. Derivative simulants can be formed by addition of component(s) that contain a glassy phase, as well as other processing.

5.3.3 Root Lunar Polar Simulant: Mixture of Low-Ti Mare Basalt and High-Ca Highland Anorthosite

Relatively little is known about the compositional identity of the lunar polar regions, although the presence of cratered terrain and mare basin features suggests that a reasonable interpretation is to expect a mixture of mare basalt and highland anorthosite material at these locations. This interpretation is also supported by the Apollo and Clementine missions that have provided orbital compositional mapping data. The polar regions of the Moon are of great interest because of the potential for subsurface water ice in the permanently shadowed regions of craters, for which some evidence was provided by the Clementine and Lunar Prospector missions. These regions are therefore likely sites for future exploration (see Figure 5.1).

Thus, it is prudent to develop a root simulant that addresses the characteristics of the lunar polar regions. Our best estimate is that a mixture of mare basaltic and highland anorthositic material is present. A root lunar polar simulant can be constructed from a mixture of SLRS root simulants of mare basalt and highland anorthosite materials. By using the simulants discussed above, it is possible to provide the solution for the need for a SLRS polar material.
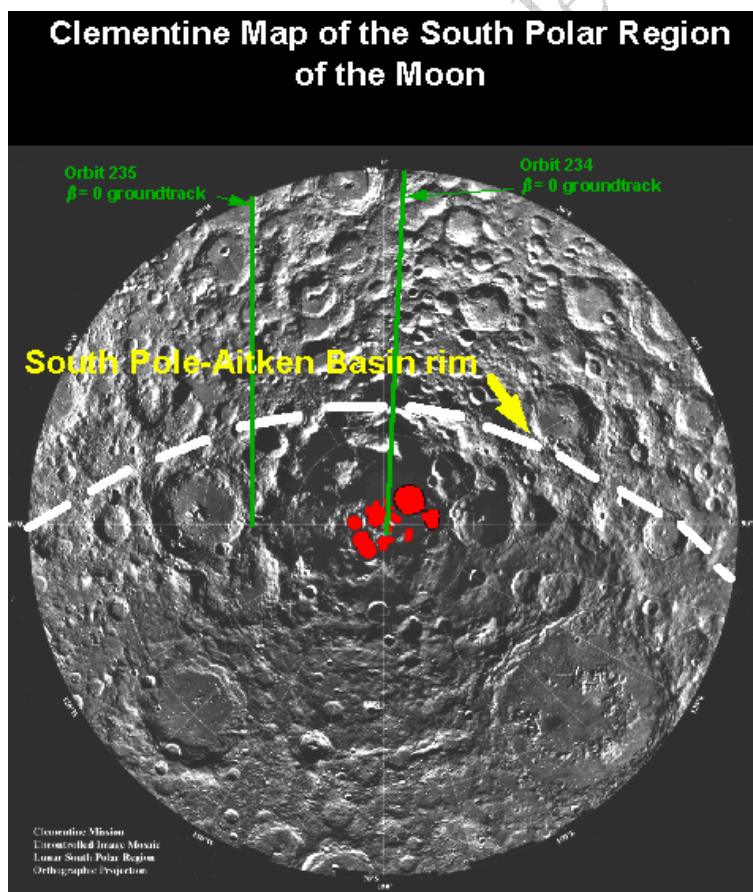
Figure 5.1. Clementine Image of Lunar South Pole Region with Possible Ice Location and Limit of South Pole-Aitken Basin Rim. Note predominance of cratered lunar highland terrane and dominance of Aitken Basin features.

5.3.4   Recommended Derivative Simulants: Additive Components

There is a clear need for mare basalt and highland anorthosite simulants. The implementation of well-chosen terrestrial materials such as a low-Ti volcanic ash of basaltic composition can accommodate the need for compositional and textural features such as a glassy fraction. A highland anorthosite simulant will require the addition of a glassy component as this will not be a feature of a terrestrial anorthosite source material.

A derivative simulant is formed from one or more root simulants and has added components that increase the simulant fidelity, compared to the lunar regolith. An evaluation of the necessary properties and characteristics of lunar regolith materials has identified the following important components that will need to be added to root simulants to produce derivative simulants.

5.3.4.1   Additive Component: Glass Fraction

Meteorite impact processes are responsible for most weathering processes on the Moon. These impact events have produced impact-melt glasses in both mare and highland materials. Glasses such as the orange and green glasses have been produced by fire fountain eruptions. The glass fraction of the lunar regolith is significant and should be reproduced in simulants in order to achieve good fidelity. Plasma melting of root simulant and/or synthetic material can be used to generate a glass population that is physically mixed with the root to form a derivative.

5.3.4.2   Additive Component: Agglutinates

Impact processes on the Moon have resulted in crushing and fragmentation of the regolith, and welding of small grains to form larger glassy agglutinates in the lunar soil. These agglutinates comprise up to 60% of the soil and are thus an important component. These agglutinates also contain nanophase iron in lunar soils in a concentration that is a reflection of the soil maturity. Agglutinates may be synthetically produced by fusion of simulant particles and physically mixed with a root simulant to form a derivative.

5.3.4.3   Additive Component: Nanophase Iron

Nanophase iron particles are produced during impact events from material that is evaporated and subsequently condensed. The reducing environment of the Moon causes iron to be reduced to the metallic state in the process, and lunar soils are characterized by nanophase iron that is typically embedded in agglutinates and smaller particles. It is anticipated that synthetic production of agglutinates can be performed in a reducing environment in order to also produce nanophase iron particles. Again, synthetic agglutinates which contain nanophase iron can be physically mixed with a root simulant in order to produce a derivative.

5.3.4.4 Additive Component: Shocked Grains

Meteorite impact processes have produced significant mechanical crushing, shocking, and melting of rock and mineral grains in the lunar regolith. Shocked grains behave differently in terms of physical and chemical properties compared to unshocked grains. This feature can be produced by high velocity impact using a projectile on a root simulant material, or by other means that may produce quantities of shocked material sufficient for simulant use. A derivative simulant is formed by addition of shocked material obtained from these techniques.

5.3.4.5 Additive Component: Solar Wind Volatiles

The lunar regolith has been exposed to the solar wind over the geologic history of the Moon. The churning action of meteorite impacts has served to periodically expose new soil grains to the solar wind. Concentration of implanted solar wind species is expected in the sub-surface layers of grains that have been exposed in this way. Ion species can likewise be implanted into terrestrial or synthetic minerals and glasses, then physically mixed with a root simulant to form a derivative.

5.3.4.6 Additive Component: Dust Fraction

The three main types of particles found in the smaller size fraction (below 50 μm) of the lunar regolith should be reproduced in SLRS materials. These include glass fragments of average composition found in lunar samples, mineral fragments representative of the major minerals (olivine, plagioclase, pyroxene, opaque minerals), and glass microspheres. The addition of these components in an SLRS material may be accomplished by further milling or grinding of a root SLRS and/or may require the synthesis of specific components. In order to obtain reduced surfaces, the preparation of these simulants should include the fracture of such materials under non-oxidizing atmospheres or vacuum. Both the materials used and preparation methods should be standardized to elaborate reference materials with known characteristics.

5.3.4.7 Additive Component: Minerals

The bulk chemistry and mineralogy of the lunar regolith is compositionally more restricted than terrestrial materials, but the environmental conditions under which it formed are unique to the Moon. For those reasons, basaltic and anorthositic root simulants can only address the basic bulk chemistry of lunar materials. The addition of mineral and glass components has been discussed, i.e., using a low-Ti basalt as a root simulant and targeting a lunar soil with a higher Ti content by addition of ilmenite. As illustrated in Tables 5.1 and 5.2, a root simulant can be used and a target soil composition can be obtained by adding mineral separates. The addition of mineral components thus is central to the adjustment of chemistry and mineralogy and should be utilized in generating derivative simulants.

5.4   **Consensus Support for Root Simulant Model Versus Alternatives**

The 2005 Workshop participants were asked to indicate their level of support for the root simulant model compared to alternative models. Criticisms and improvements of the root simulant model were also solicited during the workshop and in the time since the workshop. The general consensus in response to this question was that the root simulant model is superior in the ability to target a range of regolith properties and compositions, and that a better alternative was not known.

In breakout sessions, the participants concentrated on a proposed list of root simulants that would best achieve the needs of the community for research and technology development for activities that perform physical or chemical processing of the regolith, as well as activities that required attention to the problem of dust.

The workshop discussion included alternative views on this topic. The properties requirements matrix used by the workshop attendees positioned lunar surface activities against material properties and required an evaluation of simulants based on both perspectives. The selection of simulant materials requires an evaluation of available terrestrial source materials and their ability to address the properties requirements. An alternative view was discussed, namely, the possibility of defining material properties followed by a selection of materials that address each property. The summary of these discussions was that terrestrial source material selection was conceptually more straightforward than selection of multiple materials that would sequentially address individual properties. Further discussion of this point should be pursued in the future.

The group informally approved the root simulant model and no other alternative models were proposed for further discussion.

The use of standardized simulant materials (i.e., SLRS materials) as outlined in this section was supported by the group. There was a clear understanding among the participants of the need to utilize standards in current and future research and technology development programs. Retrospective views of historical development have revealed insufficient interlaboratory comparisons and missing information regarding simulant materials. It was agreed that SLRS materials would serve to eliminate these past problems.

5.5   **User Requirements Based on Applications**

Attendees of the 2005 Workshop were asked to provide requirements data, based on anticipated activities and applications on the Moon. These data were used to populate the properties requirements matrix from an applications perspective, and ranged from activities that were primarily physical in scope, such as excavation and drilling, to activities that were primarily chemical in scope, such as volatile extraction and oxygen extraction. The dependence of material properties of simulants were ranked as related to these activities, and has been used to prioritize the properties that are critically important for simulant development for both NASA programmatic as well as user activities.

In general, the requirements definitions for the simulant materials have included both the anticipated landing sites and the anticipated geological materials at those sites, as well as material properties that are critical for activities that are expected to be performed at these sites. Requirements have been extracted from the current knowledge database as summarized in the Lunar Sourcebook, as well as from other published scientific and engineering data related to lunar materials. These requirements are supplemented by those identified by users at the 2005 Workshop, with a focus on activities-driven requirements.

During the 2005 Workshop, attendees ranked the lunar regolith properties based on their expertise and assessment of requirements that were critical for the development of lunar regolith simulants. This assessment is summarized in Table C.1, Appendix C, where the order of importance is ranked, with the specific regolith property and the consensus count of votes obtained using an electronic polling system. This polling system also provided for extended input of justification and discussion of the evaluation that took place in breakout sessions for activities that were primarily physical, chemical, and dust-related in scope.

It should be emphasized that Table 2.2 contains only those material properties of the lunar regolith that must be possessed by SLRS materials as determined by expert consensus at the 2005 Workshop. According to this consensus, these properties must be duplicated with medium or high fidelity.

This ranking has been used for evaluation of simulant requirements both for short and long term simulant development. Inspection of the ranking reveals that both physical/geotechnical and chemical/mineralogical requirements can be satisfied by selection of simulant source materials followed by processing that results in basic root simulant materials. For example, of the physical requirements, grain size and grain size distribution, particle density, bulk density, grain shape, magnetic properties, and strength characteristics were ranked highest in the order listed. For chemical requirements, the compositional and mineralogical characteristics of glass, bulk chemistry, and modal composition were ranked highest, or in the order listed. These requirements are mutually in agreement, so that for a given simulant material such as anorthosite, the density and compositional characteristics are in agreement and not exclusive. Properties that are grain-specific rather than referring to bulk properties have also been ranked higher since bulk properties such as shear strength depend on the degree of assembly of soil particles in addition to the nature of the simulant material.

The ranking of properties bears additional discussion based on subsequent developments since the workshop was held in January 2005. At the time of the workshop, the knowledge base of the community concerning lunar regolith simulant development was less complete than at the present. The ranking required an assessment of properties that required either medium or high degree of fidelity in simulants compared to the lunar regolith. These ranked properties are intended to be used for the development of root simulants rather than derivative simulants, and for this reason the importance of agglutinates and nanophase Fe appears low in the list when it is clear that these are critically important properties for evaluation of derivative simulants that have high fidelity compared to the lunar regolith.

From this evaluation of requirements, selection of a basaltic mare simulant, an anorthositic highland simulant, and a mixed mare and highland polar simulant could be implemented and would satisfy the ranked list in Table C.1, Appendix C. This ranking also reveals that a minimum of processing is required in order to produce the high priority requirements. In particular, milling and sieving of the raw simulant material would produce the grain size and grain size distribution properties. This high level ranking of properties is consistent with a simulant development plan where root simulants are developed using terrestrial source materials and are processed by crushing, grinding, and sieving methods to produce the sizing characteristics of the lunar regolith.

Subordinate physical and chemical properties could be accommodated by development of derivative simulants. For example, implantation of solar wind components, production of agglutinates, and incorporation of nanophase Fe ranked at a lower priority based on the group assessment. These properties naturally fit into a derivative simulant development scenario and would likely be produced in lesser quantities for specific applications.

5.6   Root Simulant Calculations: Constructing Targeted Simulants from Root Components

Linear least-squares analysis of chemistry data has been used to perform a best fit of proposed root simulants compared to target soil compositions. In this procedure, each root simulant contributes to the total chemistry budget for an element such as Fe; the best fit mixture is one that matches all elements in the targeted soil composition. Two examples of this approach are included below. In Table 5.1, an example using root mineral simulants is modeled in a physical mixture to match an Apollo 16 highland sample (*Carpenter*, 2005). A least squares match is made based on oxide chemistry of each mixed component, and is performed using an olivine of Fo_{92} composition (a typical terrestrial olivine of composition ($Mg_{1.84}Fe_{0.16}Si_2O_4$), pure anorthite ($CaAl_2Si_2O_8$), and quartz ($SiO_2$). This least squares match is made relative to the bulk chemistry of the highland sample.

As can be seen, it is a simple matter to achieve the Ca content of the target by adjusting the proportion of anorthite alone, but the adjustment of Mg and Fe is controlled by the proportion of olivine, and the best match is for Mg rather than for Fe. In general, it is difficult to achieve good matches for Fe as FeO due to the higher oxidation state of terrestrial source materials, as seen in this example. The best mineral match using this example is for a mix of 16% olivine Fo_{92}, 78% Plagioclase An_{100}, 6% quartz, which clearly resembles the mineralogy of an anorthosite. Note that some source of SiO_2 is required to match the highland chemistry as both olivine and anorthite are deficient in SiO_2 and no combination can be used to raise the Si content. This example suffers from two objections. First, the mixture of mineral separates does not duplicate the complex textures and lithic features of the lunar regolith. Secondly, quartz is rare on the Moon and this mixture would not be representative of the modal abundance of a highland soil from that perspective.

A second example illustrates the hypothetical use of lunar simulant JSC-1 in physical mixtures with mineral separates obtained from JSC-1 material (Table 5.2). These minerals include ilmenite, olivine, a Ca-pyroxene, plagioclase, and basaltic glass. The least squares match for

mixtures of these materials is made relative to a high-Ti Apollo 11 basalt, an Apollo 14 KREEP basalt, and the same Apollo 16 highland anorthosite as used in the previous example. As JSC-1 was selected based on similarity to the Apollo 14 chemistry, a reasonably good match can be made at 100% JSC-1 simulant. For each target, a simple match using JSC-1 and a minimum of additional mineral separates is made, and is compared with more complex mixtures that achieve better matches as measured by the least squares parameter R_{min}, for which the lowest value is the best match to the target.

This example illustrates that it may be possible to utilize JSC-1 as a root simulant for a specific target, and that conceivably by extraction of mineral separates and recombination with the parent, it is possible to adjust the composition in order to achieve incrementally better matches. For example, a high-Ti Apollo 11 basalt can be approximated by adding ilmenite from JSC-1 to bulk JSC-1 simulant in the amount of 14 parts ilmenite for 86 parts of JSC-1. This approach thus requires only JSC-1 material as a source, but requires efficient separation of material that would inevitably contain impurities and make implementation of this approach complicated. Furthermore, the constituent minerals in JSC-1 are of a fine grain size, and a large quantity of JSC-1 simulant would be required in order to produce the mineral separates. For these reasons, it will be preferable from the standpoint of mineral beneficiation to utilize source materials that allow production of large quantities of the desired mineral, such as ilmenite beach sands or olivine collected from dunite (an olivine rock).

This approach to date has not included other factors such as mineral chemistry and grain size distribution. The more generalized approach of linear programming should be utilized in order to evaluate selection of root materials based on a set of properties. The most critical comments that can be made concerning existing simulants JSC-1 and MLS-1 is that while the bulk composition matches discrete Apollo compositions, the mineral chemistry is not formally matched in the procedure. It is also necessary to mill the simulants in order to achieve the grain size distribution of the lunar soils.

The practical issues of root simulant selection are dictated by available geological source materials. These source materials should be compositionally similar to lunar compositions, homogeneous enough to allow removal of multi-tonnage quantities without observing significant variation in chemical and physical properties, be geographically located in the United States, and be actively mined so that fresh material can be conveniently obtained.

Based on these considerations, the concept of a root simulant is a material that in raw form is compositionally similar to the targeted regolith composition, and requires a minimum of further processing in order to achieve a match. This minimum processing is anticipated to be milling and sieving in order to match the grain size distribution of lunar soils.

**6.0   RECOMMENDATION 2: ESTABLISH A PROCESS FOR
          DEVELOPMENT, PRODUCTION, AND CERTIFICATION OF
          STANDARD LUNAR REGOLITH SIMULANT MATERIALS**

The production of SLRS materials will require a coordinated effort beginning with an evaluation of the quantities of simulant needed by the science and engineering communities, followed by the selection of appropriate source materials, and ending with delivery of final standardized simulant products. It will be necessary to acquire material, perform initial test screening, ramp up for production, characterize the material during phases of production, package, store, and distribute the simulant to end-users. Strict quality control procedures will be necessary during all phases of the process. The 2005 Workshop recommended that NASA established such a process to guarantee the availability of SLRS materials.   The following sections describe the recommended activities of this process.

6.1   Estimates of Simulant Quantities Needed for Research and Testing

The estimation of simulant quantities for planning purposes is a topic of ongoing discussion. Activities which are primarily physical in scope, such as excavation and drilling, will require test beds or "sand boxes" that can equate up to tens of tons of simulant. Conversely, activities which are primarily chemical in scope, such as volatile extraction, will likely require smaller quantities of simulant. Initial estimates solicited from users have resulted in large estimates, but follow-up dialogue has resulted in significant reduction in those estimates, especially as funding issues have entered into the discussion.

For illustrative purposes it is helpful to know that 1 ton of simulant represents a cube of material approximately 70 cm (i.e., 2 ft) on a side, and 10 tons of simulant occupies the space of a typical office desk. Note that these volumes may change for material that is more or less porous than the volcanic ash from which JSC-1 has been made (density estimates for this material are 3000 kg per m^3 (187 lbs per ft^3). When one considers the volume of material that is anticipated for a wide range of applications that include both physical activities such as excavation and drilling, and chemical processing techniques that destructively consume simulant in kilogram quantities, it becomes apparent that quantities approaching 100 tons may be necessary for the research and testing communities.

Activities that will utilize simulants can be classified as either non-destructive or destructive. Destructive processes will clearly require a fresh batch of simulant for each subsequent test of a process. These destructive tests do not necessarily destroy the simulant, but may irrevocably change the simulant characteristics. For example, construction tests incorporate simulant into a block using a binder so that the simulant may be essentially unmodified but is mixed with a foreign material so that it cannot be broken down and reused as a SLRS material. Activities such as excavation, drilling, and vehicle testing that require the initial setup of a test bed will require a large quantity of simulant, and may require additional material if the simulant is broken down or modified. It is anticipated that while technologies are in the early stage of demonstration, significant consumption of simulant will take place as techniques are identified and refined. Thus, it is likely that the largest quantities of SLRS materials are necessary at the beginning of testing programs, but as these programs mature, smaller quantities will be necessary based on the

assumption that efficient use of material will prevail as flight demonstrations are achieved. It is implicit in these discussions that many processes will operate on small quantities of material in order to achieve efficiency of operation on the Moon or Mars.

6.2   Simulant Requirements Definition and Specifications

The development of SLRS materials begins with the definition of simulant requirements. These requirements must contain specific information regarding the chemical, mineralogical, physical, and geotechnical properties that must be addressed in the final simulant product. For example, the requirements for a root basalt simulant include bulk properties such as chemistry, mineralogy, grain size distribution, and bulk or relative density, as well as specific properties such as grain shape and modal composition as a function of grain size. The requirements for a given root or derivative simulant must be specific in establishing target ranges of values in order to achieve the highest fidelity compared to the target soil. The requirements will be used to evaluate candidate geological source materials from which SLRS materials can be produced against specification that describe their geological location and exact range of values for each property.

6.3   Simulant Source Material Selection

During the selection of appropriate terrestrial materials, it is important to consider the chemical, mineralogical, and physical materials as mentioned. The selection of source materials should be performed using a quantitative analysis method that permits the inclusion of all appropriate requirements properties in order to best match the targeted lunar regolith. This procedure is illustrated in Section 5.6, Root Simulant Calculations: Constructing Targeted Simulants from Root Components, but can be expanded to include matching of source materials to a target material by use of a comprehensive set of requirements that include, for example, compositional, physical, and spectral data in the match procedure. Simulants can thus be designed with differing emphases on characteristics which allow tailoring of the simulant to the activity or landing site.

This procedure ultimately is used to identify a geological source material which can be obtained from a rock or mineral deposit, or from materials that were mined and purified. Material that is present in a geological deposit must be mined or removed from the quarry. It is desirable to utilize a geological deposit that is actively mined as this will typically ensure that fresh, unweathered rock and mineral material is chosen, and will minimize the incorporation of altered material.

Preliminary discussions with mining companies have been very favorable and the personnel from these companies have demonstrated a commitment in support of NASA's exploration program.

6.4   Initial Batch Screening and Characterization

Once a geological source for simulant material has been identified, it is necessary to evaluate the material in small test batches for the properties prior to a full-scale production run. This initial

batch screening is used to determine that the source rock and mineral properties are as expected if assumptions are made about the nature of the material. This batch screening is used to evaluate the suitability and homogeneity of the material, and to also determine what additional processing is required in order to bring the simulant in line with requirements such as grain size distribution. For practical purposes, it is expected that milling and sieving of the raw simulant is performed at a facility near the quarry. All aspects of simulant production must be identified prior to the batch screening stage, so that the main production run differs only in scale of operation and does not institute different techniques that may result in deviations in the simulant properties from the requirements document.

Simulant characterization techniques are outlined in Section 6.11, Characterization Techniques.

6.5   Simulant Production and Characterization

Initial batch testing is necessary to evaluate whether the selected material is in fact appropriate for use as a simulant. The material should be characterized and processed at this stage using the same appropriate chemical, mineralogical, physical, and geotechnical techniques that will be used for the production run. An emphasis must be placed not only on adherence to requirements properties, but also on determining the homogeneity of the material at different scales.

The 2005 Workshop discussion included the concepts of simulant grade, and the identification of bulk grade, technical grade, and research grade simulant. These grades represent increasing fidelity of the simulant compared to the lunar regolith. This information is covered in Section 6.12, Simulant Grade Options: Bulk Grade, Technical Grade, and Research Grade.

Once initial batch testing has been performed and the material passes the requirements for development as a root simulant, a full-scale production run can be initiated. During the main production run, simulant is acquired from the quarry, moved to the milling facility, milled or physically crushed, and further processed in the same manner that was used during the initial screening run. During the processing operation it is important to perform characterization of the simulant and to hold the simulant until characterization is completed. The simulant batches should be placed in an environmentally controlled holding area while physical, chemical and mineralogical characterization methods are used to demonstrate compliance with the simulant requirements. Simulant samples should be split for characterization methods and for archival of simulant removed from the production run at this stage. These samples should be used to monitor simulant homogeneity at the production stage.

The characterization methods used at this stage are intended to demonstrate compliance with requirements and to document homogeneity at the scale of production. Documentation of actual variability in the simulant will be made at the packaging stage, where it is expected that due to the nature of the simulant as a natural soil, variability will be observed.

After this characterization step, when it is clear that each batch complies with the requirements, the simulant will be released for movement to the packaging facility.

6.6　　　　　　　Simulant Packaging and Characterization

Simulant material that leaves the processing facility exists in large batches for the purposes of transportation.　At the packaging facility, the simulant will be split into smaller batches, homogenized, and samples drawn off as the simulant is mixed and allocated for final packaging. Several types of mixing equipment are available for homogenizing the simulant prior to packaging.　The preferred equipment mixes material in an end-over-end manner and includes cone or v-blender equipment.　The use of food grade stainless steel mixing equipment, similar to portable cement mixers, is not as desirable due to contamination issues from the stainless steel, but is a convenient method for handling hundred kilogram quantities of simulant and also allows for sampling at this level.　For simulant production, a trace contaminant of stainless steel, typically at the hundreds of parts per million, can be tolerated since iron is a major element in the mare basalts and nanophase iron is a desirable component of a high fidelity simulant material. The samples drawn for characterization at this step will be used to track the actual variability that remains in the properties of the simulant.　Because the simulant is a natural material with a grain size distribution like the lunar soil, it is by definition not a homogeneous material.　Therefore, it is expected that variability of properties will be observed as the sample size is continually reduced.　These issues are well known in the geological community based on experience with standard reference rock powders, where these reference materials are ground to a fine powder in order to remove chemical variability due to persistence of grains that have markedly different chemistry in the fine powder.

Simulant material is placed in the final package for distribution and characterization samples are pulled from the simulant supply at this step.　These samples are used to track the variation in properties and establish the certificate values for the simulant.　Small batches of packaged simulant will share a common certificate using this sampling technique.　Each packaged container will have a label that indicates the simulant name with other descriptive information, and documents the lot and package number in the production sequence.　The certificate will be provided separately and will serve several purposes.　First, the certificate also identifies the material including a tracking number for identification of the lot and package.　Secondly, the simulant is calibrated against the master set of requirements in a traceable manner using the characterization data.　Thirdly, the simulant package, which includes the documentation, forms a quality control link that provides proof of the authenticity of the simulant material.　This authentication must be maintained by the end user in order to eliminate errors due to labeling and storage in secondary containers in the test facility.　Due to the powdered nature of the simulant, this is necessary as different materials appear similar after processing.　It should be emphasized that the simulant is certified in terms of tracking information and characterization data, but that this certification also provides proof of authenticity for use as a standardized testing material.

6.7　　　　　　　Quality Control of SLRS Materials

The preceding sections emphasize the need to comply with simulant requirements during production, and to obtain a simulant product that is homogeneous to the extent possible for a natural soil.

Lessons learned from experience with simulant MLS-1 are particularly important with regard to quality control issues. The distributed MLS-1 simulant did not fully match the grain size distribution for lunar soils and required additional grinding based on grain size matching to bring the distribution in line with the distributions for Apollo soils. This highlights the need to perform characterization at the processing stage before proceeding to the packaging stage.

There are also sampling issues as highlighted by chemical analysis of MLS-1 simulant. The consistency of bulk chemistry for geochemical reference standards depends on a consistent fine grain size. Bulk chemical analysis of small sample populations of MLS-1 reveal wide variations at the major and trace element level, which reflects improper sampling of material as well as grain size issues. This aspect is important for standard reference rock powders, where occasional large grains of an accessory phase cause a spike in concentration in analyses (e.g., Cr variation due to modal variations in chromite). Likewise, the presence of grains of quartz in an anorthosite powder would cause uneven measurements of geotechnical properties that depend on mineral hardness. Homogenization is important for both physical and chemical properties of simulant materials and it is necessary to address both aspects in quality control during simulant production. This homogenization is ensured for geochemical reference standards by grinding the material to a fine grain size. It is necessary to do this for samples of simulant that have been pulled from the production run for chemical analysis. A sample size that is sufficiently large must be used for research or engineering activities in order to adequately represent the range of mineralogy in the simulant.

6.8 Curation, Storage, Shelf Life, and Long Term Monitoring of SLRS Materials

The simulant material in packaged form will require a program of curation, storage, and a mechanism for distribution and tracking of simulant that has been transferred to end-users. A curator will have the responsibility of receiving requests for simulant that have been approved by the controlling agency and transferring a simulant package to that individual. The curator also has the responsibility of tracking simulant that has been requested, distributed, and monitoring the status of distributed material if that is necessary.

The simulant must be stored in an environmentally controlled facility that has minimal variation in temperature and humidity. The production of SLRS materials will require quality control procedures that establish adherence to simulant requirements and specifications during processing and during packaging for storage and/or distribution to end users. It is important to deliver a simulant product to end users that continues to comply with the requirements set forth, thus, there are issues of *compliance* during production and packaging, and *maintainability* of the simulant properties after packing and during storage. Simulant materials contain phases that will react with water vapor. The fine grained size fraction in particular must be kept in an anhydrous state to avoid reaction and clumping of material. Reaction with water vapor can therefore cause both chemical and physical changes to the simulant as both mineralogical reactions and grain size modifications may take place. As the simulant materials are a physical mixture of a range of grain sizes, it is also important to limit exposure of packaged simulant to vibration which would cause differential grain settling to take place. Technical discussions have suggested that packaging modifications would anticipate a degree of settling and that rehomogenization instructions be provided to users to limit this problem.

For these reasons, it is prudent to store simulant materials in climate controlled facilities that have restricted humidity, temperature, and vibration conditions. For the root SLRS materials discussed by the 2005 Workshop, highly reactive material such as nanophase Fe grains would not be in the distributed simulant. However, derivative simulants which contain nanophase Fe will need to have this material stabilized against reaction with atmospheric water. This could be accomplished by incorporation of the nanophase particles within glassy material or by vacuum packaging. The need for a simulant that combines regolith simulant with water ice for evaluation of activities involving polar regions will clearly require that either the user mix regolith with ice prior to testing, or that premixed regolith and ice will be provided and maintained as a frozen mixture for distribution.

Sensitivity of the SLRS materials to modification by environmental variables is an aspect of simulant curation and storage that must be monitored in an ongoing manner. It may be necessary to analyze simulant materials after prolonged storage as part of the quality control regimen in order to demonstrate the maintained compliance with requirements.

6.9   Distribution Issues for SLRS Materials

A well developed plan for distribution of SLRS materials is important. Distribution involves responsibilities that may span a significant time range and require record keeping for the purposes of tracking both simulant packages and end users. Experience with the distribution of JSC-1 has shown that little is known about which individuals received simulant, what quantities were distributed, what quantity of original stock remains after 10 years, and what research activities it supports.

The distribution responsibility for JSC-1 has been transferred to different individuals and no formal records of distribution exist. Distribution of simulant is conducted by serially drawing material from master batches. Any variation in properties that are identified after distribution cannot be clearly described without a complete record of distribution. The absence of such records and lack of traceability for JSC-1 had led to the confusion regarding unlabeled batches with unknown origin compared to the original JSC-1 material.

An electronic database offers a convenient solution to distribution record keeping and matching of simulant to users. This database can be used by the curator, the Simulant Science Advisory Committee (SSAC), and end users, with appropriate viewing privileges, for the purposes of tracking and monitoring simulant use.

6.10   Safety Issues for SLRS Materials

Simulant materials will include a dust fraction that will inherently be present in all samples. The presence of a dust size component which can become airborne is of particular concern. The need to match the modal composition of the lunar dust requires that dust simulants contain a large concentration of silicate minerals. The known toxicological hazards associated with silica dust require that similar safety precautions be taken by users of these simulants. Without taking appropriate precautions, these airborne SLRS dust particles could be distributed throughout

experimental facilities leading to contamination and abrasion issues for instrumentation, and dust ingestion by humans. A dust simulant would, for obvious reasons, require greater attention to these issues since the entire simulant will be in the fine size range compared to simulants that contain a fractional percentage of dust. For these reasons, it is anticipated that both dust and regolith SLRS materials will require a Material Safety Data Sheet (MSDS) in order to provide documentation of potential hazards and to guide users in simulant use.

6.11 Characterization Techniques

Characterization of SLRS materials is necessary using physical, chemical, and mineralogical methods. To date, the characterization of simulant materials has not been implemented at the same level of effort expended to characterize the existing lunar sample inventory. Indeed, sample processing techniques and analytical methods have been developed specifically for the study of lunar samples owing to their priceless nature and need to consume as little material as possible during analysis. Analysis of lunar samples has therefore been almost entirely non-destructive. Methods were calibrated against baseline measurements on selected material and then applied more widely.

<u>Analysis of SLRS materials will need to be performed using primarily bulk chemical and physical methods, but also will include microanalytical techniques</u>. Bulk chemical analysis is used to evaluate the chemistry of simulant samples and to reflect the compositional makeup of the simulant material without specific information regarding mineralogy. Researchers that need to study processes that occur over different size scales can use both bulk and microanalytical techniques to monitor the beginning of a reaction which likely begins at the micro scale and proceeds to larger sample volumes. Failure analysis of a wide range of natural and synthetic materials reveals that the physical, chemical, and phase-specific properties at the micro-scale determine the failure of, and subsequently, the material behavior of the bulk sample. It is therefore important to understand the nature of simulant materials on both the micro and macro scales.

The analytical techniques are outlined as follows.

6.11.1 Bulk Chemical Analysis

In similar fashion to the analysis of lunar materials, bulk analysis of simulant materials should be analyzed by non-destructive techniques if possible. Non-destructive bulk chemistry techniques include XRF spectrometry, which can be utilized for major, minor, and trace element analysis, and also offers the possibility of real-time analysis during process monitoring. Newer microsource x-ray tubes with a 10-50 μm spot size permit a similar mapping strategy as discussed for Electron-Probe Microanalysis (EPMA). Instrumental Neutron-Activation Analysis (INAA, non-destructive) and inductively coupled plasma mass spectrometry (ICP-MS, requires sample digestion) can also be used for trace analysis. <u>It is important to analyze both major and trace element profiles during simulant characterization, as the trace element abundances can be a sensitive indicator of sample inhomogeneity, grain settling during processing, and contamination from components of the processing equipment</u>.

### 6.11.2	Mineralogical Characterization

Analysis of simulant materials using powder XRD is necessary to evaluate the identity of minerals present in the simulant, and can also be used to extract the volumetric, or modal, abundance of the minerals. This information is critical in determining the mineralogy of the simulant and can be coupled with mineral chemistry data obtained from EPMA to calculate the bulk chemistry of the simulant. This serves as a comparison with bulk chemistry and also determines the internal consistency of the simulant analysis.

Advances in powder XRD include Rietveld analysis, a whole-pattern fitting technique which provides a powerful tool for characterization of lunar simulants when coupled with quantitative phase analysis. Rietveld analysis provides the modal abundance of minerals as well as the cell refinement data that forms a fundamental set of characterization data for other studies. Real-time phase and structural changes at elevated temperatures can be monitored using a high temperature XRD furnace attachment.

### 6.11.3	Physical Characterization Methods

The characterization of physical properties of simulant materials includes geotechnical analytical methods. These methods include both bulk methods and methods that evaluate properties on a per grain analysis of the simulant. Bulk geotechnical methods include sieve analysis, where the simulant is separated into the grain size ranges for comparison with the grain size distribution curves for lunar regolith materials. Grain shape analysis is an evaluation of the shape factors for grains and requires analysis of the materials on a per grain basis. The characterization of the max/min void ratios and the use of relative density instead of bulk density (see Table 2.1) is recommended to promote standard comparisons of SLRS materials with the lunar regolith. In addition to characterizing their constituents, SLRS materials should also be characterized to compare their geotechnical behavior to that of the lunar regolith. Therefore, the measurement of engineering properties such as strength (i.e., friction angle and cohesion intercept) and elastic moduli (i.e., Young's modulus, shear modulus, and Poisson's ratio) is recommended.

### 6.11.4	Microanalytical Characterization Methods

Modern analytical techniques bridge the spatial range from "bulk" to "microanalytical" by means of micro-sampling. EPMA has been used to obtain nearly all mineralogical analyses of returned lunar samples. The development of the technique and application to lunar materials represents a milestone in quantitative microanalysis. In addition to microanalysis of lunar minerals, the bulk chemistry of lunar samples was obtained using EPMA by means of a point count measuring protocol based on a grid of sampling points on the polished sample. As the number of grid points was increased, both the individual mineral chemistry and the bulk chemistry estimates improved in comparison to baseline bulk chemistry techniques. Modern microprobe systems have benefited from numerous improvements in instrumentation and automation in the 35 years since Apollo. Current systems can routinely collect digital backscattered-electron and x-ray maps using beam deflection as well as stage point counting methods. Digital images can be used for size analysis, in which derivative images are analyzed in order to extract grain size and shape

measurements. This can be coupled with simultaneous chemical typing of grains and serves to support other bulk measurements made using geotechnical methods. This parallel analysis can readily illustrate the need, for example, to perform additional grinding of lunar simulant MLS-1 in order to establish a finer grain size fraction and bring the simulant in line with targeted Apollo soil characteristics. In the last decade, secondary-ion mass spectrometry (SIMS) has been used extensively to perform trace element analysis of lunar materials and can also support lunar simulant characterization needs.

6.11.5 Characterization of Dust Simulant

Dust SLRS materials are by definition the fraction of material that is less than 50 µm in size. The characterization of this dust fraction has to date required techniques such as wet sieving or grain size determination using laser methods. These methods can only be used to characterize dust materials as they modify the material in the process and are therefore unsuitable for production and separation of the dust fraction. Non-destructive techniques will be required for dust characterization and separation. Techniques used in environmental monitoring of airborne particles involving the ratio of charge to mass determination will likely prove to be useful in this effort. Bulk chemical methods are expected to be similar for both classes of material, but microchemical methods such as electron-probe microanalysis will be necessary in order to characterize individual grains.

6.12 Simulant Grade Options: Bulk Grade, Technical Grade, and Research Grade

Discussions by 2005 Workshop attendees included an evaluation of simulant development using the concept of grading, similar to that used for commercially produced chemical reagent materials. In this system, bulk grade simulants would represent materials that are suitable for primarily physical processes. Potentially, they would have the lowest fidelity compared to lunar regolith materials, but would be least expensive to produce and could be made available in large quantities at a lower cost compared to the other grades. Technical grade would represent an intermediate simulant material that has been processed to an additional degree in order to more closely approximate the lunar regolith, and therefore would be a material with intermediate fidelity. Finally, research grade simulant would represent material that has the highest possible fidelity and would most closely approximate or duplicate the properties of the lunar regolith.

6.12.1 Bulk Grade Option

Bulk grade simulant materials are considered to be those simulants that could be used for scientific and engineering work where the process under consideration depends primarily on the physical properties of the simulant, with significantly reduced dependence on chemical properties. For example, excavation, drilling, and abrasion tests would generally fall under processes that may use bulk grade simulants early in their development. The bulk grade simulants would in general not be appropriate for evaluation of processes that are chemical in scope, such as volatile extraction or element purification studies that would require both the chemical and mineralogical fidelity of simulants to more closely match the lunar regolith. It is

anticipated that bulk grade material would be produced in the largest quantity and would require a less rigorous quality control regimen during production. Bulk grade simulant would be most appropriate for general distribution and, for example, use in the educational NASA outreach system.

6.12.2   Technical Grade Option

Technical grade simulant materials are those simulants that require a higher fidelity of simulation of the lunar regolith than bulk grade. Simulants at the technical grade could be used for scientific and engineering testing where the process under consideration depends both on the physical and chemical properties of the simulant. The dependence on mineralogical properties of the simulant would in general need to be evaluated for the process being studied. It is likely that technical grade simulants could be used during the early development stages of studies which evaluate chemical extraction, where simulant material would be consumed in larger quantities as the techniques are refined. Only when the technique has matured or demonstrated efficiency would research grade simulant material be used for final testing. Technical grade simulants would in principle represent root simulants that have had additional modification, such as the addition of microspherical glass and synthetic agglutinates to a root simulant. A modification of this type would represent a higher degree of fidelity using a process of physical addition of material at relatively low additional cost. It is anticipated that technical grade material may be produced in a smaller quantity compared to bulk grade, and would require a comparatively more rigorous quality control regiment during production. Technical grade simulant would be most appropriate for testing during maturation of techniques.

6.12.3   Research Grade Option

Research grade simulant materials are those simulants that require the highest fidelity of simulation of the lunar regolith compared to bulk and technical grade. Simulants at the research grade would be used for scientific and engineering testing where the process under consideration depends on close approximation or actual duplication of the physical, chemical, and mineralogical properties of the simulant. Research grade simulants would be used during the final stages of studies which evaluate chemical extraction, where simulant material would be consumed in small quantities to demonstrate the final efficiency of the technique. Research grade simulants would in principle represent derivative simulants that may also have additional modifications, such as the physical addition of components such as synthetic agglutinates, but also may include chemical processing such as modification of the oxidation state of iron in order to duplicate the mineralogy of the lunar regolith. These research grade materials may also be comprised of materials that in part make use of samples from the existing lunar sample inventory, such as lunar dust, and would not necessarily represent material that would be destructively consumed. The research grade simulants would likely be produced in the smallest quantity compared to bulk and technical grade materials, and would require the most rigorous quality control regiment during production.

7.0   RECOMMENDATION 3: DEVELOP A LONG-TERM SIMULANT ACQUISITION STRATEGY

NASA's Apollo Program successfully implemented a purposeful policy of selection, standardization, and usage of lunar reference simulant materials to develop and test new lunar technologies. This historical approach should be implemented by NASA as part of the robotic and human exploration of the Moon, Mars, and beyond. <u>The 2005 Workshop participants and the Workshop Science Advisory Committee strongly recommend that NASA adopt a specific policy for the acquisition and usage of simulant materials for all its projects of technology development for planetary surface missions. Such a policy is necessary to correct current trends that will lead to a proliferation of non-standard simulant materials and their indiscriminate use</u>. Issues that have not been adequately addressed in the scientific and engineering communities are requirement specifications for acceptable standard simulant materials, the continuous improvement of these materials based on new lunar science data, and the usage of standard materials by NASA sponsored projects. Lessons learned from past efforts, workshop discussions, and subsequent post-workshop activities have led to the recommendations in the following paragraphs. Figure 7.1 illustrates the task structure proposed by NASA/MSFC to realize an effective SLRS development and acquisition based on the recommendations.

7.1   Establish an Advisory Committee on Simulant Materials

A Simulant Science Advisory Committee (SSAC) should be formally created, charged and supported by NASA to provide scientific expertise on all issues pertaining to simulating the characteristics of planetary materials to be encountered by NASA space missions and to carry out the following functions:

   a. Advise on the types of SLRS materials needed to reflect NASA's chronological priorities as defined in the space exploration architecture. At the present time, work on defining lunar simulant materials should precede work on martian simulant materials.
   b. Advise NASA on the specific requirements for various simulant materials.
   c. Advise NASA as to the acceptable range of values for each simulant physical, chemical and mineralogical property.
   d. Issue recommendations on which simulants should receive NASA/USGS certification and the use of these SLRS materials in NASA sponsored projects.
   e. Make recommendations on the improvement of existing SLRS materials based on new lunar and martian science data and new information on the limitations reported by projects on their usefulness.
   f. Assist NASA in identifying potentially new simulant types and forecasting expected user needs required to support future NASA sponsored projects.
   g. Assist in the organization of workshops on lunar and Mars simulant materials to assess the state of research using lunar and martian simulants and disseminate new information.

The SSAC should include, but not be limited to, members with expertise in planetary science (Moon, Mars, asteroids, etc.), development of geochemical standard reference materials, and materials science. The committee should meet regularly to perform its functions and issue its recommendations to NASA.
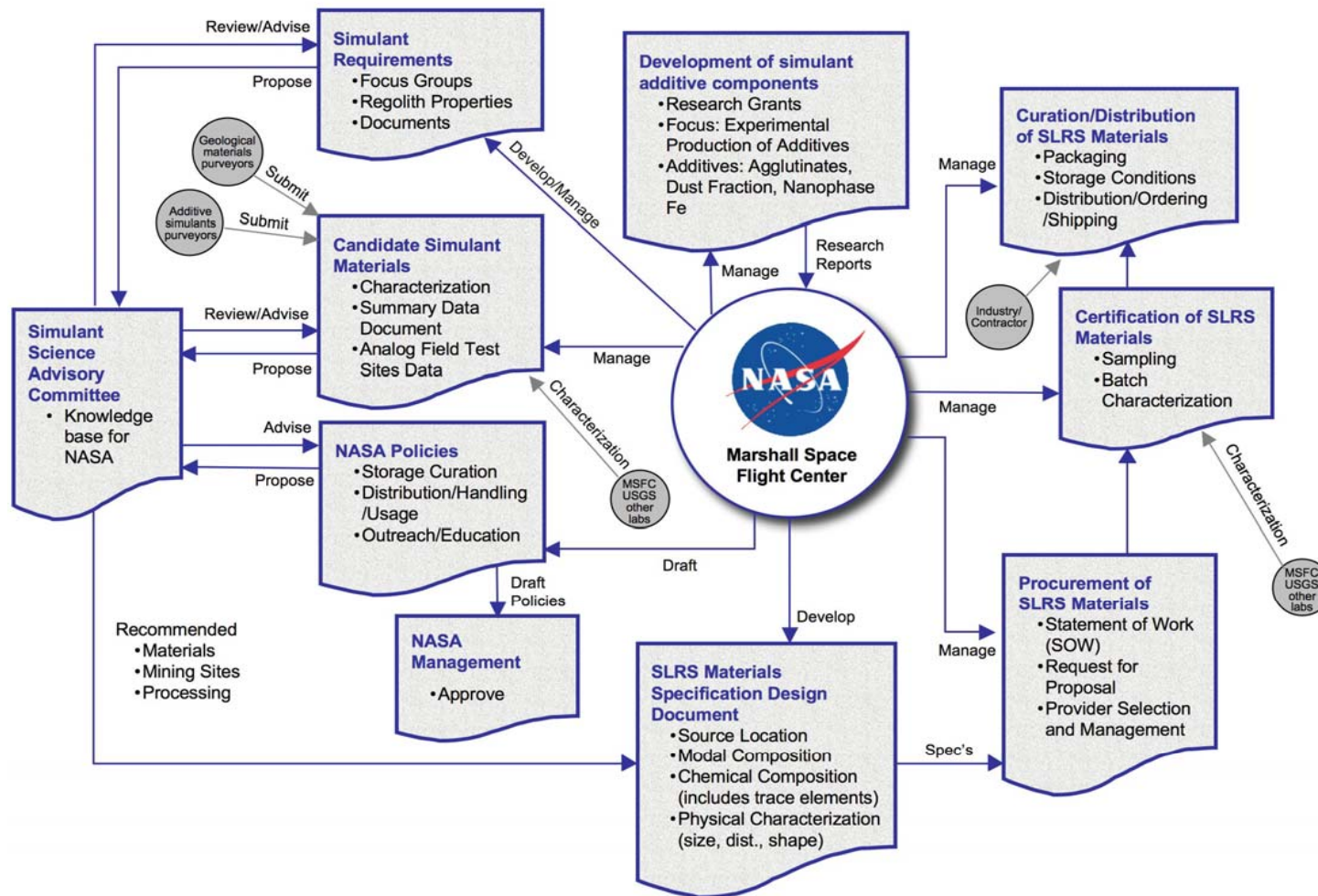
Figure. 7.1 Acquisition and Certification of Standard Lunar Regolith Simulant Materials. This illustration depicts the role of MSFC in coordinating the tasks required to make standardized simulant materials available to NASA-sponsored projects. The important roles of MSFC partners in this effort are also identified.

7.2 Policies for the Development of SLRS Materials

NASA Headquarters management should identify the appropriate NASA organization to lead the development, characterization, and standardization of simulant materials for the Agency. This NASA organization should be responsible for establishing policies related to the procurement, quality-control, certification, storage, distribution, and usage of simulant materials for NASA sponsored projects.

7.2.1 Requirements for SLRS Materials

A requirements document for SLRS materials will be published in conjunction with this report. The data collected and assembled in the simulant materials requirements document represents the present state of knowledge and should be updated as that knowledge evolves. The importance of requirements on specifications for lunar regolith simulants must not be underestimated. Well-designed requirements and specifications will allow researchers and technology developers to compare technologies and designs necessary for successful lunar operations.

7.2.2 Developmental Research on Selected Simulant Materials

Several critical components of the lunar regolith are not available in any existing simulant materials; agglutinates, nanophase iron, solar-wind volatiles, and micron-size dust particles. Furthermore, these characteristics are not found in geological source materials on Earth. The development of such components should be initiated through directed research tasks funded by NASA to establish the feasibility of fabrication techniques, and to characterize and validate the produced materials against lunar samples.

7.2.3 SLRS Materials Certification Process

NASA should establish an approval and certification process for simulant materials that are needed for NASA sponsored projects. Recommended materials should be developed as SLRS to ensure that these materials are characterized appropriately prior to being made available to users. This process should be established in collaboration with the USGS as soon as possible. NASA should require certification for all simulant materials developed or recommended for use by NASA sponsored projects. Final approval of a SLRS material for use on a NASA sponsored project should be the sole responsibility of NASA.

The development and characterization of SLRS materials in multi-tonnage quantities should be undertaken first, for which quality control procedures are put in place, to produce consistent simulants with particular emphasis on homogeneity at the appropriate scale. Secondly, the development of a lunar dust SLRS material must be undertaken for specialized research and testing purposes. Additionally, the same materials chosen to generate SLRS materials (e.g., mare basalt and highland anorthosite) should also be used to produce geochemical reference powders that are appropriate for analytical calibration. Finally, an ongoing program of glass-forming studies and the production of microanalysis standards for EPMA should be pursued.

Collaborative research between NASA (specifically MSFC) and the USGS is already an integral part of planning for simulant development activities and the establishment of SLRS materials. USGS standard reference materials are rock and mineral powders that have been finely ground in order to achieve chemical homogeneity, and are used as primary and secondary chemical standards for analytical procedures. The expertise that the USGS has attained in their long-standing geochemical standard reference material program is being utilized for planning and development of lunar simulants, for which the physical and chemical properties of the lunar regolith are important to duplicate. The USGS should collaborate with NASA to implement the certification of SLRS materials recommended in this report under the guidance of the SSAC.

Restrictions and exceptions on SLRS materials should be identified and controlled by the appropriate NASA organization.

7.2.4   Quality Control of SLRS Materials

NASA is the final authority as to whether a simulant material meets the NASA SLRS specifications and whether the simulant material used is appropriate for a NASA sponsored project. To support this, NASA should establish a robust simulant materials quality control process.

7.2.5   Storage, Distribution, and Reuse of SLRS Materials

NASA should set standards for the storage and distribution of material to be used on NASA sponsored projects. The purpose of the policy should be to control the chemical and physical makeup of the simulant material before it is used to ensure that the simulant material meets the standards of its original certification.

The minimization of moisture uptake in the simulant material is an important component of the storage process. While efforts should be taken to produce a material that has a minimum absorbed water content, the simulant should be stored in a dry, humidity controlled facility. Procedures such as drying the simulant before use may be required based on other specific issues that become known during simulant development.

Once simulant material is used, its physical and chemical properties could be affected due to certain transformation processes such as crushing, the addition of moisture and/or foreign materials or the release of certain volatiles. This transformation of the simulant material may cause a de-certification of the SLRS material, making it inappropriate for further use in NASA sponsored projects.

7.2.6   Use of SLRS Materials by NASA Sponsored Projects

NASA sponsored projects requiring simulant materials should only use SLRS materials certified by NASA. Certification and characterization of SLRS materials should be done under the supervision of the appropriate NASA organization and in collaboration with the USGS.

NASA should publish a set of guidelines as soon as possible to help organizations needing SLRS materials to obtain, store, use, and dispose of these materials.

7.2.7   Use of SLRS Materials by Non-NASA Sponsored Projects

Industry and academia organizations requiring simulant materials are encouraged to utilize SLRS materials for their projects. Industry and academia projects wishing to receive NASA certification for their simulant are encouraged to coordinate their simulant certification with the NASA organization responsible for the certification of simulant materials. Organizations using non-standard and/or non-certified simulant materials may find it difficult to compare their experimental project data and remain on an even footing with projects utilizing certified SLRS materials.

7.2.8   Tracking of SLRS Material Usage

To support the continuous development of better simulant materials, it is recommended that NASA maintain a database of the types of projects, experiments or studies utilizing SLRS materials, the types of simulant materials required and/or used by the project, the expected outcome, and the actual results of the project, experiment or study. NASA should encourage all NASA organizations, industry, and academia to contribute to this database.

7.2.9   Procurement of SLRS Materials

NASA should encourage industry, academia, and government to establish reliable sources and methods for producing SLRS materials that meet NASA and USGS standards. Established NASA procurement processes and practices should be utilized in the procurement of simulant materials from commercial sources when practical. Non-NASA organizations should be permitted to obtain simulant materials meeting NASA certification from commercial suppliers.

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8.0 BIBLIOGRAPHY

Adams, J.H. and Bhattacharya, M. (2005) Space Radiation and Lunar Regolith. *Abstracts for Lunar Regolith Simulant Materials Workshop,* p.1.

Agosto, W. N. (1984) Electrostatic Separation and Sizing of Ilmenite in Lunar Soil Simulants and Samples (abstract). *Lunar and Planetary Science XV,* pp 1-2.

Allton, J.H. (1989) Catalog of Apollo Lunar Surface Geological Sampling Tools and Containers. *NASA Johnson Space Center Document JSC-23454.*

Allton, J.H., Galindo, C., and Watts, L.A. (1985) Guide to using lunar soil and simulants for experimentation. *Lunar bases and space activities of the 21st century, Lunar and Planetary Institute*, pp. 497-506.

Anderson, E.D., Patchen, A., Cahill, J.T., and Taylor, L.A. (2001) Mineral Modes in Fine Fractions of Lunar Highlands Soils: Experimentation with Subjective Parameters of "FeatureScan". *Meteoritics & Planetary Science*, volume. 36, Supplement, p.A11.

Baird, J.K. (2005) Supercritical Extraction of Metals Using Binary Liquid Mixtures with a Consolute Point. *Abstracts for Lunar Regolith Simulant Materials Workshop,* pp.31-32.

Basaltic Volcanism Study Project (1981) *Basaltic Volcanism on the Terrestrial Planets*. Pergamon Press, Inc. New York.

Basu, A., McKay, D. S., Morris, R.V., and Wentworth, S.J. (1996) Anatomy of individual agglutinates from a lunar highland soil. *Meteoritics*, volume. 31, pp 777-782.

Basu, A., Wentworth, S.J., and McKay, D.S. (2000) Grain-size Distribution of Apollo 11 Soil 10084, *31st Annual Lunar and Planetary Science Conference,* abstract no. 1306.

Basu, A., Wentworth, S.J., and McKay, D.S (1999) A Petrologic Comparison of Apollo 11 Soil 10084 and Disaggregated Regolith Breccia 10068. *30th Annual Lunar and Planetary Science Conference,* abstract no. 1873.

Bates, A., Coscio, M.R., and Murthy, V.R. (1975) Episodic Lunacy-VI: Trace Element Studies on Grain-Size Fractions of Lunar Soils and the A-17 Deep Drill Core. *Abstracts of the Lunar and Planetary Science Conference*, volume 6, p. 28.

Batiste, S.N. and Sture, S. (2005) Lunar Regolith Simulant MLS-1: Production and Engineering Properties. *Abstracts for Lunar Regolith Simulant Materials Workshop,* pp.2-3.

Bazilevsky A.T., Grebennik N.N., Gromov V.V. *et al*. (1984) Dependence of Physical and Mechanical Properties of the Lunar Soil upon Specific Relief and Processes in Operation Sites of Lunokhod-2'. *Kosm. Issled.*. Vol.XXII, N2.

Berney, E.S. and Peters, J.F. (2005) The In-situ State: The Elusive Ingredient in Lunar Simulant. *Abstracts for Lunar Regolith Simulant Materials Workshop,* p.4.

Beaty, D. W., Coradini, A., Clifford, S., Grant, J., Gogineni, P., Plaut, J., Raney, K., and Safaeinili, A. (2001), Analysis Of The Potential Of A Mars Orbital Ground-Penetrating Radar Instrument In 2005. *A White Paper.*

Benoit, P.H., Batchelor, J.D., Symes, S.J., and Sears, D.W.G. (1994) Primitive Material in Lunar Highland Soils. *Abstracts of the 25th Lunar and Planetary Science Conference*, p.97.

Blacic, J.D. (1985) Mechanical Properties of Lunar Materials Under Anhydrous, Hard Vacuum Conditions: Applications of Lunar Glass Structural Components. *Lunar Bases and Space Activities of the 21st Century., Lunar and Planetary Institute*, p.487.

Boslough, M. B., Bernold, L. E., and Horie, Y. (1992) Shock-treated lunar soil simulant: Preliminary assessment as a construction material. *Lunar and Planetary Inst., Joint Workshop on New Technologies for Lunar Resource Assessment,* pp 14-15.

Boudreau A. (1999) PELE--a version of the MELTS software program for the PC platform. *Comp. & Geosci.* 25(2): p p.201-203.

Butler, J.C. and King, E.A. (1974) Analysis of grain size-frequency distributions of lunar fines. *Proc. Lunar Sci. Conf. 5th,* pp 829-841.

Carpenter, P. (2005) Characterization Strategies and Requirements for Lunar Regolith Simulant Materials. *Abstracts for Lunar Regolith Simulant Materials Workshop,* pp.5-6.

Carrier, W.D. (1973) Lunar Soil Grain Size Distribution. *Earth, Moon, and Planets*, volume. 6, p.250.

Carrier, W.D., Olhoeft, G.R., and Mendell, W. (1991) Physical properties of the lunar surface, *Lunar Sourcebook*, Ed. Cambridge University Press, Ch. 9.

Carter, J.L., McKay, D.S., Allen, C.C., and Taylor, L.A. (2005) New Lunar Simulants: JSC-2 (JSC-1 Clone) and JSC-3. *Abstracts for Lunar Regolith Simulant Materials Workshop,* pp.7-8.

Carusi A. et al. (1972) Lunar glasses as an index of impacted sites lithology: The source area of Apollo 15 "green glasses". *Geol. Romana* 11, 137.

Chambers, J.G., Taylor, L.A., Patchen, A., Mckay, D.S. (1995) True Modal Analyses of Lunar Mare Soils: X-Ray Digital-Imaging. *Abstracts of the Lunar and Planetary Science Conference*, volume 26, p. 227.

Chang, S., Lennon, K., and Gibson, E.K. (1976) Distribution of Sulfur, Helium, and Magnetic Particles in Grain Size Fractions of Lunar Soils. *Abstracts of the Lunar and Planetary Science Conference*, volume 7, p. 123.

Charette, M.P., Taylor, S.R., Adams, J.B., and McCord, T.B. (1977) The detection of soils of Fra Mauro basalt and anorthositic gabbro composition in the lunar highlands by remote spectral reflectance techniques. *Proc. Lunar Sci. Conf. 8th*,. volume 1, pp. 1049-1061.

Cole, D.M., Shoop, S., and Corcoran, P.T. (2005) Lunar Regolith Simulant Requirements: Mechanical Properties Considerations. *Abstracts for Lunar Regolith Simulant Materials Workshop,* p. 9.

Craig, R.F. (1992) *Soil Mechanics*. Ed, Chapman and Hall 5th Edition.

Crouch, D.S. (1968) Apollo Lunar Surface Drill (ALSD) Final Report. *Report ER 14778, NASA George C. Marshall Space Flight Center (NAS9-6587).*

Darquenne, C., Paiva, M., West,J.B., and Prisk, G.K. (1997) Effect of microgravity and hypergravity on deposition of 0.5 to 3 micron-diameter aerosol in the human lung. *J. Appl. Physiol*. 83, pp. 2029-2036

Debelak, K.A., Lynch, D.C., Sibille, L., and Sadoway, D.R. (2005) Towards Lunar Simulants Possessing Properties Critical to Research and Development of Extractive Processes. *Abstracts for Lunar Regolith Simulant Materials Workshop,* p. 24.

Eick, M.J., Grossl, P.R., Golden, D.C., Sparks, D.L., and Ming, D.W. (1996a) Dissolution of a lunar basalt stimulant as affected by pH and organic anions. *Geoderma 74*. pp. 139-160.

Eick, M.J., Grossl, P.R., Golden, D.C., Sparks, D.L., and Ming, D.W. (1996b) Dissolution kinetics of a lunar glass simulant at 25°C: The effect of pH and organic acids. *Geochimica et Cosmochimica Acta*, volume 60, Issue 1, pp.157-170.

Engelhardt, W.V. (1994) Apollo 16 Lunar Glasses: Normative Composition and Origin. *Abstracts of the 25th Lunar and Planetary Science Conference*, p.351.

Engelhardt, W.V., Hurrle, H., and, Luft, E. (1976) Microimpact-induced changes of textural parameters and modal composition of the lunar regolith. *Proc. Lunar Sci. Conf. 7th*,. Volume 1. pp. 373-392.

Englert, P. A.J., Drake, D.M., Shunk, E.R., Drosg, M., Reedy, R.C, and Bruckner, J. (1990) Simulation of Galactic Cosmic Ray Interactions with 'Martian soil': Implications for Cosmogenic Nuclide Studies and Planetary Gamma Ray Spectroscopy. *Abstracts of the Lunar and Planetary Science Conference,* volume 21, p 325.

Evensen, N.M., Murthy, V.R., and Coscio, M.R. (1974) Provenance of KREEP and the exotic component - Elemental and isotopic studies of grain size fractions in lunar soils. *Proc. Lunar Sci. Conf. 5th,*. volume 2, pp. 1401-1417.

Fischer, E.M., Pieters, C.M., McEwen, A.S., Head, J.W., and Belton, M.J.S. (1992) Lunar Highland Soil Heterogeneity: Al/Si Estimated for the Limb and Farside from Galileo SSI and Apollo X-Ray Spectrometer Data. *Abstracts of the Lunar and Planetary Science Conference*, volume 23, p. 361.

Foley, N.C., Economou, T., and Clayton, R.N. (2003) Final chemical results for the Mars Pathfinder alpha proton x-ray spectrometer. *J. Geophys. Res.*, volume 108, No. E12, 8096.

Friebele, E.J., Griscom, D.L., Marquardt, C.L., Weeks, R.A., and Prestel, D. (1974) Temperature dependence of the ferromagnetic resonance linewidth of lunar soils, iron and magnetic precipitates in simulated lunar glasses, and nonspherical metallic iron particles. *Proc. Lunar Conference, 5th* volume 3, pp. 2729-2736.

Gaier, J.R.. (2005) The Effects Of Lunar Dust On Advanced EVA Systems: Lessons From Apollo**. *NASA TM—2005-213610.*

Ghiorso, M.S. and Sack, R.O. (1994) Chemical Mass Transfer in Magmatic Processes. IV. A Revised and Internally Consistent Thermodynamic Model for the Interpolation and Extrapolation of Liquid-Solid Equilibria in Magmatic Systems at Elevated Temperatures and Pressures. *Contributions to Mineralogy and Petrology*.

Graf, J. (1990) Fractal Grainshape Analysis of Lunar Soils 67941 and 68501. *Abstracts of the Lunar and Planetary Science Conference*, volume 21, p. 429.

Green, A.J., Melzer, K.J. (December 1971) Performance of Boeing LRV wheels in a lunar soil simulant. Report 1: Effect of wheel design and soil. *Technical Report M-71-10, US Army Engineer Waterways Experiment Station*.

Griscom, D.L., Marquardt, C.L., and Friebele, E.J (1974) Ferromagnetic Resonance of Fine Grained Iron and Magnetite Precipitates in Simulated Lunar Glasses: Comparison with Lunar Soils. *Abstracts of the Lunar and Planetary Science Conference,* volume 5, p 293.

Gunderson, K., Whitby, J., and Thomas, N. (2005) Visible and NIR BRDF Measurements of Lunar Soil Simulant. *36th Annual Lunar and Planetary Science Conference*, abstract no.1781.

Haskin, L.A., Korotev, R.L., Lindstrom, and M.M. (1980) Highlands Olivine Norite, a Major Constituent of Lunar Highlands Soils. *Lunar and Planetary Science XI*, p. 413-415. Abstract.

Hayes, S.A., Bustin, R.M., and Allen, C.C. (1995) Reduction of Iron Oxides in Simulated Lunar Soil Using Carbon as the Reducing Agent. *Abstracts of the Lunar and Planetary Science Conference,* volume 26*, page 565.

Heiken, G.H., Vaniman, D.T., and French, B.M. (1991) *Lunar Sourcebook – A User's Guide to the Moon.* Cambridge University Press, New York.

Horai, K. and Winkler, J. (1978) Effect of Interstitial Gaseous Pressure on Thermal Conductivity of Apollo 12 Simulant Lunar Soil. *Lunar And Planetary Science IX, Abstract.* pp. 534-536.

Horanyi, M., Walch, B., and Robertson, S. (1998) Electrostatic Charging of Lunar Dust. *29th Annual Lunar and Planetary Science Conference,* abstract no. 1527.

Hutcheson, L., Butler, T., Smith, M., Cline, C., Scruggs, S., and Zakhia, N. (1987) Soil Experiment. *ME4182, Mechanical Design Engineering, NASA/University, Advanced Missions Space Design Program, Georgia Institute of Technology.*

Hutton, R.E. (1969) Lunar Surfaces Models. *NASA SP-8023.*

Jolliff, B.L. (1991) Compositional Variations of Particles from North Ray Crater Soil 67513 and Implications for the Composition of the Lunar Highlands. *Abstracts of the Lunar and Planetary Science Conference*, volume 22, p. 653.

Keller, L.P. and McKay, D.S. (1997) The nature and origin of rims on lunar soil grains. *Geochimica et Cosmochimica Acta.* volume 61, number. 11, pp. 2331-2431.

Keller, L.P., Wentworth, S.J., McKay, D.S., Taylor, L.A., Pieters, C., and Morris, R.V. (2000) Space Weathering in the Fine Size Fractions of Lunar Soils: Mare/Highland Differences. *31st Annual Lunar and Planetary Science Conference*, abstract no. 1655.

Kerschmann, R.L. (2005) Biological Effects Of Lunar Surface Mineral Particulates. *Abstracts for Lunar Regolith Simulant Materials Workshop,* p.13.

Kraehenbuehl, U., Gruetter, A., Gunten, H.R.V., Meyer, G., Wegmuller, F., and Wyttenbach, A. (1977) Distribution of Volatile and Non-Volatile Elements in Grain-Size Fractions of Apollo 17 Lunar Soils. *Abstracts of the Lunar and Planetary Science Conference*, volume 8, p. 561.

Laul, J.C. and Papike, J.J. (1980) The lunar regolith: Comparative chemistry of the Apollo sites. *Proc. Lunar Planet. Sci. Conf. 11th*, pp. 1307-1340.

Laul, J.C., Vaniman, D.T., Papike, J.J. and Simon, S. (1978) Chemistry and petrology of size fractions of Apollo 17 deep drill core 70009-70006. *Proc. Lunar Planet. Sci. Conf. 9th*, pp. 2065-2097.

Lembeck, Michael F. (2005) *Exploration System of Systems Technical Requirements Document, ESMD-RQ-0010, Rev E,* 30 March, 2005. NASA publication.

Lindsay, J.F. (1973a) Evolution of lunar soil grain-size and shape parameters. *Proc. Lunar Sci. Conf.*, volume 4, p.215.

Lindsay, J.F. (1973b) Evolution of Lunar Soil Grain-Size Parameters. *Abstracts of the Lunar and Planetary Science Conference*, volume 4, p. 472.

Liu, Y., Taylor, L.A., Thompson, J.R., Patchen, A., Hill, E., and Park, J. (2005) "Lunar Agglutinitic Glass Simulants with Nanophase Iron", *Proceedings of the Space Resources Roundtable VII*: *LEAG Conference on Lunar Exploration, October 25-28, 2005*.

Lofgren, G.E. (2005) Sintering, Melting and Crystallization Of Lunar Soil With An Experimental Petrologic Point Of View. *Abstracts for Lunar Regolith Simulant Materials Workshop,* pp.14-15.

Lowman, P.D. (2005) Composition Of The Lunar Highland Crust: A New Model. *Abstracts for Lunar Regolith Simulant Materials Workshop,* p.16.

McKay, D.S. (2005) Evolution Of The Lunar Regolith. *Abstracts for Lunar Regolith Simulant Materials Workshop,* pp.17-19.

McKay, D.S., Basu, A., Waits, G., Clanton, U., Fuhrman, R., and Fruland, R. (1977) Grain Size and Evolution of Luna 24 Soils. *Abstracts of Papers Presented to the Conference on Luna 24. LPI Contribution 304*, p.114.

McKay, D.S., and Blacic, J.D. (1991) Workshop on Production and Uses of Simulated Lunar Materials. *LPI Technical Report 91-01*.

McKay, D.S., Fruland, R.M., and Heiken, G.H. (1974) Grain size and the evolution of lunar soils. *Proc. Lunar Sci. Conf. 5th*, volume 1, pp. 887-906.

Meek, T.T., Vaniman, D.T., Blake, R.D., and Godbole, M.J.(1987) Sintering of Lunar Soil Simulants Using 2.45 GHz Microwave Radiation. *Abstracts of the Lunar and Planetary Science Conference,* volume 18, p 635.

Meeker, G.P. (2005) Characterization Of Chemical And Physical Properties Of Proposed Simulant Materials. *Abstracts for Lunar Regolith Simulant Materials Workshop,* pp.20-21.

Menard, J., Sangillo, J., Savain, A., and McNamara, K. M. (2004) Effects of Subsurface Sampling & Processing on Martian Simulant Containing Varying Quantities of Water. *35th Lunar and Planetary Science Conference*, abstract no.1202.

Mendez, C., Garza, E., Gulati, P., Morris, P. A., and Allen, C. C. (2005) Isolation and Identification of Microorganisms in JSC Mars-1 Simulant Soil. *36th Annual Lunar and Planetary Science Conference*, abstract no.2360.

Milliken, R.E., and Basu, A. (2000) A Modified CIPW Norm Calculation for Lunar Mare Basalts. *31st Annual Lunar and Planetary Science Conference*, abstract no. 1427.

Morris, R.V. (1977a) Fine-Grained Metal Distribution in Grain-Size Separates of Lunar Soils: Production and Evolution of the Fine-Grained Metal. *Abstracts of the Lunar and Planetary Science Conference*, volume 8, p. 682.

Morris, R.V., (1977b) Origin and evolution of the grain-size dependence of the concentration of fine-grained metal in lunar soils - The maturation of lunar soils to a steady-state stage. *Lunar Proc. Lunar Sci. Conf. 8th,.* Volume 3. p. 3719-3747.

Morris, R.V., Korotev, R.L., Shelfer, T.D, and Klingelhofer, G. (1997) Mossbauer Mineralogy on the Moon: The Lunar Regolith. *NASA CR-97-112965* and *Hyperfine Interactions.*

Morris, R.V., Agresti, D.G., Wills, E.L., Shelfer, T.D., Pimperl, M.M., Shen, M.-H., and Gibson, M. A. (1992) Mössbauer spectroscopy for lunar resource assessment: Measurement of mineralogy and soil maturity. *Lunar and Planetary Inst., Joint Workshop on New Technologies for Lunar Resource Assessment,* p 39-40.

Mullis, C.H. (1971) A study and analysis of the MSFC Lunar Roving Vehicle dust profile test program., *Report No. 139-92, NASA George C. Marshall Space Flight Center (NAS8-26715).*

Nakagawa, M., Agui, J.H. and Angel, H. (2005) The Moon as a Beach of Fine Powders. *Abstracts for Lunar Regolith Simulant Materials Workshop,* pp.22-23.

Omar, H.A. Production of Lunar Concrete Using Molten Sulfer. *Final Research Report for JoVe NASA Grant NAG8-278.*

Papike, J.J., Ryder, G., and Sharer (1998) Lunar Samples. *Reviews in Mineralogy, Planetary Materials, volume 36.*

Papike, J.J., Simon, S.B., and Laul, J.C. (1982) The lunar regolith: Chemistry, mineralogy, and petrology. *Rev. Geophys. Space Phys., 20*, pp. 761-826.

Pieters, C.M., Stankevich, D.G., Shkuratov, Yu. G., and Taylor, L.A. (2001) Statistical Analysis of the Links among Lunar Mare Soil Mineralogy, Chemistry, and Reflectance Spectra. *Icarus,* volume 155, Issue 2*,* pp. 285-298.

Perkins, S.W., and Madson, C.R. (1996) Mechanical And Load-Settlement Characteristics Of Two Lunar Soil Simulants. *J. Aerospace Engineering*, volume. 9, pp. 1-9.

Prinz, M., Dowty, E., Bunch, T.E., and Keil, K. (1973) Mineralogy, petrology and chemistry of lithic fragments from Luna 20 fines: origin of the cumulate ANT suite and its relationship to high-alumina and mare basalts. *Geochimica et Cosmochimica Acta.* volume 37, Issue 4, pp. 979-1006.

Raedecke, L.D., and McCallum, I. S. (1980) A comparison of fractionation trends in the lunar crust and the Stillwater Complex. *Proc. Conf. Lunar Highlands Crust*, pp. 133-153.

Reddy, R.G., Tong, L., and Sen, S. (2005) Thermodynamic Modeling and Experimental Studies on Planetary Materials. *Abstracts for Lunar Regolith Simulant Materials Workshop,* p.33.

Reid, A. M. (1974), Rock Types Present in Lunar Highland Soils, *The Moon, 9*, p. 141-146.

Reid, K.J., Knight, R., Murawa, M.J., and Pridgeon, J. (1987) Characteristics of High-Power SSP Magnetically Rotated Electric Arcs. ISPC-8, Tokyo. Paper number P-035, pp.453-459.

Salisbury, J.W., Basu, A., and Fischer, E.M. (1997) Thermal Infrared Spectra of Lunar Soils. *Icarus,* volume 130, Issue 1*, pp. 125-139.

Semenova, A. S., Kononkova, N. N., and Guseva, E. V. (1991) Highland Component in the Luna 16 Soil. *Abstracts of the Lunar and Planetary Science Conference*, volume 22, p. 1215.

Sibille, L. (2005) The Status of Lunar Simulant Materials, Workshop Overview and Objectives. *Abstracts for Lunar Regolith Simulant Materials Workshop,* p.25.

Sickafoose, A.A., Colwell, J.E., Horanyi, M., and Robertson, S. (2002) Dust Levitation in a Plasma Sheath Near a Surface. *33rd Annual Lunar and Planetary Science Conference*, abstract no.1743.

Simoes, F, Trautner, R., Grard, R., Hamelin, M. (2004) Laboratory Measurements on Martian Soil Simulant JSC Mars-1 Supporting the Calibration of Instruments for Planetary Missions. *Proceedings of the 37th ESLAB Symposium `Tools and Technologies for Future Planetary Exploration', (ESA SP-543).* pp.205-209.

Synder, G.A., Neal, C.R., Jain, J. and Taylor, L.A. (1997) A "Stormy" Sortie for Pristine Rocks in Lunar Soils: 2. Trace-Element Compositions of Coarse-Grained "Highlands" Rocks from Apollo 12. *Conference Paper, 28th Annual Lunar and Planetary Science Conference,* p. 351.

Snyder, G.A., Taylor, L.A., and Patchen, A. (1996) A Sortie for Pristine Moon Rocks from Oceanus Procellarum: 2. Cumulate 'Highlands' Gabbros from Soil 12001. *Lunar and Planetary Science*, volume 27, p. 1239.

Spudis, P. (2005) Lunar Science Overview. *Proceedings of the Space Resources Roundtable VII*: *LEAG Conference on Lunar Exploration, October 25-28, 2005.*

Tatom, F.B., Srepel, V., Johnson, R.D., Contaxes, N.A., Adams, J.G., Seaman, H., and Cline, B.L. (1967) Lunar Dust Degradation Effects and removal/prevention concepts – final report, volume II – Detailed results. *Northrop/Huntsville Technical Report No. 323, NASA George C. Marshall Space Flight Center (NAS8-20116 and NASA-CR-94044).*

Taylor, G. Jeffrey (1/19/2005) Lunar Exploration Analysis Group (LEAG) Report (personal communication).

Taylor, L.A. (1990) Rocks and minerals in the regolith of the Moon: Resources for a lunar base. *Advanced Materials—Applications of Mining and Metallurgical Processing Principles* (V.I. Lakshmanan, ed.), pp.29-47. Society for Mining, Metallurgy, and Exploration, Littleton, Colorado.

Taylor, L.A. (2005) Physical and Chemical Characteristics of Lunar Regolith: Considerations for Simulants. *Abstracts for Lunar Regolith Simulant Materials Workshop,* pp.26-27.

Taylor, L.A., Cahill, J.T., Patchen, A., Pieters, C., Morris, R.V., Keller, L.P., and McKay, D.S. (2001) Mineralogical and Chemical Characterization of Lunar Highland Regolith: Lessons Learned from Mare Soils. *32nd Annual Lunar and Planetary Science Conference*, abstract no.2196.

Taylor, L. A., Carrier, W.D., and Taylor, G.J. (2005) The Geotechnical Properties of the Lunar Regolith: From Equator to the Poles. *Abstracts for Lunar Regolith Simulant Materials Workshop,* pp.28-29.

Taylor, L.A., Chambers, J.G., Patchen, A., Jerde, E.A., McKay, D.S., Graf, J., and Oder, R.R. (1993) Evaluation of lunar rocks and soils for resource utilization: Detailed image analysis of raw materials and beneficiated products. *Lunar and Planetary Inst., Twenty-Fourth Lunar and Planetary Science Conference. Part 3*: *N-Z* p 1409-1410.

Taylor, L.A., McKay, D.S., Graf, J., Patchen, A., Wentworth, S., Oder, R., and Jerde, E. (1992) Magnetic Beneficiation of High-Ti Mare Basalts: Petrographic Analyses. *Abstracts of the Lunar and Planetary Science Conference*, volume 23, p. 1415.

Taylor, L.A., Patchen, A., Taylor, D.H., Morris, R.V, Pieters, C., Keller, L. P., Wentworth, S., and McKay, D.S. (2000) Mineralogical Characterization of Lunar Mare Soils. *31st Annual Lunar and Planetary Science Conference*, abstract no. 1706.

Taylor, L.A., Morris, R.V., Keller, L. P., Pieters, C., Patchen, A., Taylor, D.H., Wentworth, S., McKay, D.S. (2000) Major Contributions to Spectral Reflectance Opacity by Non-Agglutinitic, Surface-Correlated Nanophase Iron. *31st Annual Lunar and Planetary Science Conference,* abstract no. 1842.

Taylor, L.A., Patchen, A., Cahill, J., Pieters, C., Morris, R.V, Keller, L. P., and McKay, D.S. (2002) Mineral and Glass Characterization of Apollo 14 Soils. *33rd Annual Lunar and Planetary Science Conference,* abstract no.1302.

Taylor, L.A., Patchen, A., Taylor, D.-H.S., Chambers, J.G., and McKay, D.S. (1996) X-Ray Digital Imaging Petrography of Lunar Mare Soils: Modal Analyses of Minerals and Glasses. *Icarus,* volume 124, Issue 2, pp. 500-512.

Taylor, L.A., Pieters, C., Patchen, A., Taylor, D.-H., Morris, R.V, Keller, L. P., and McKay, D.S. (2003) Mineralogical Characterization of Lunar Highland Soils. *34th Annual Lunar and Planetary Science Conference,* abstract no.1774.

Taylor, S.R. (1975) Lunar science: A post-Apollo view. *Pergamon Press, Inc. New York,* p. 390.

Thiel, K., Damm, G., and Herr, W. (1974) Simulated cosmic-ray induced U-fission tracks in artificial lunar soil and implications for the U-238 fission track dating of lunar surface samples. *Proc. Lunar Sci. Conf. 5th,* volume 3, pp.2609-2621.

Thode, H.G. and Rees, C.E. (1976) Sulphur isotopes in grain size fractions of lunar soils. *Proc. Lunar Sci. Conf. 7th*. Volume 1. pp. 459-468.

Trosper, J. (2005) *Robotic Lunar Exploration Program Requirements Document, ESMD-RQ-0014 (Rev. A), 22 February 2005*, NASA publication.

Tucker, D.S., Ethridge, E., and Curreri, P. (1992) Glass Fiber Processing for the Moon/Mars Program. *NASA TM-108379*.

Tucker, D. and Setzer, A. (1991) Differential Thermal Analysis of Lunar Soil Simulant. *NASA TM-103563*.

Turkevich, A.L. (1973) The average chemical composition of the lunar surface. *Proc. Lunar Sci. Conf.,* volume 4, p.1159.

Vaniman, D.T., Chipera, S.J., Bish, D.L., Carey, J.W., Fialips, C.I., and Feldman, W.C. (2004) Sulfate Salts, Regolith Interactions, and Water Storage in Equatorial Martian Regolith. *35th Lunar and Planetary Science Conference,* abstract no.1690.

Vaniman, D.T., Heiken, G., Wohletz, K., and Blacic, J. (1992) Palagonites and Martian Soil Simulants. *Abstracts of the Lunar and Planetary Science Conference,* volume 23, p. 1463.

Vaniman, D.T., Meek, T.T., and Blake, R.D. (1986) Fusing Lunar Materials with Microwave Energy. Part II: Melting of a Simulated Glassy Apollo 11 Soil (abstract). *Lunar and Planetary Science XVII,* pp. 911-912.

The Vision for Space Exploration (February, 2004) NASA, NP-2004-01-334-HQ (Rev)

Warren, P.H (1986) Anorthosite assimilation and the origin of the Mg/Fe-related bimodality of pristine moon rocks: Support for the magmasphere hypothesis. *Proc. Lunar Planet. Sci. Conf. 16th in J. Geophys. Res., 91,* pp. D331-D343.

Weiblen, P.W. and Gordon, K. (1988) Characteristics of a Simulant for Lunar Surface Materials. *Abstracts of papers presented to the Second Conference on Lunar Bases and Space Activities of the 21st Century. LPI Contribution 652*, p.254.

Weiblen, P.W., Murawa, M.J., and Reid, K.J. (1990) Preparation of Simulants for Lunar Surface Materials, in: *Engineering, Construction, and Operations in Space II*, American Society of Civil Engineers, New York, volume 1, pp. 98-106.

Willman, B.M., Boles, W.W., McKay, D.S., and Allen, C.C. (1995) Properties of Lunar Soil Simulant JSC-1. *J. of Aerospace Engineering*, volume 8, No. 2. pp 77-87.

Wilson, S.A. (2005) Development of Geochemical Reference Materials at the United States Geological Survey. *Abstracts for Lunar Regolith Simulant Materials Workshop,* p. 30.

Wood, A.R. and Basu, A. (2002) Estimating Mineral Compositions of Planetary Surfaces from Chemical Compositions: A Comparison Between Modal Analysis, CIPW Normative Mineralogy, and Mixing Calculations as Applied to Lunar Mare Basalts. *33rd Annual Lunar and Planetary Science Conference*, abstract no.1739.

Worms, J.C., Renard, J.B., Levasseur-Regourd, A.C., and Hadamcik, E. (1999) Light scattering by dust particles in microgravity: the PROGRA^2 achievements and results. *Advances in Space Research*, Volume 23, Issue 7, pp. 1257-1266.

Wu, C.Y.R., Chen, F., and Judge, D.L. (1995) Total Electron Yields and Total Fluorescence Yields of Albite and Lunar Soil Simulants JCS-1 and MLS-1. *Abstracts of the Lunar and Planetary Science Conference,* volume 26*,* p. 1525.

Zheng, Y, Wang S., Li, C., Ouyang,Z., Feng, J., Liu, J. and Zhou, Y., (2005) The Development of CAS-1 Lunar Soil Simulant. International Lunar Conference 2005, Toronto, Canada. (abstract).

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Appendix A, Abbreviations and Acronyms

AEVA   Advanced Extravehicular Activity
ASTM   American Society for Testing and Materials

BAA   Broad Area Announcement

DC   Direct Current

EPMA   Electron Probe Microanalysis
ESAS   Exploration Systems Architecture Study
ESMD   Exploration Systems Mission Directorate
ESRT   Exploration Systems Research Technology
EVA   Extra Vehicular Activity

GPR   Ground Penetrating Radar
GSD   Grain Size Distribution

HSRT   Human Systems Research and Technology

ICP   Intramural Call for Proposal
ICP   Inductively Coupled Plasma
ICP-MS   Inductively Coupled Plasma Mass Spectrometry
INAA   Instrumental Neutron-Activation Analysis
ISFR   In Situ Fabrication and Repair
ISLSP   In Situ Life Support Processes
ISRU   In Situ Resource Utilization
ISSP   In-Flight Sustained Shockwave Plasma

JSC   Johnson Space Center

LEAG   Lunar Exploration Analysis Group
LEM   Lunar Excursion Module
LPI   Lunar and Planetary Institute
LRL   Lunar Receiving Laboratory
LRO   Lunar Reconnaissance Orbiter
LRV   Lunar Roving Vehicle
LSS   Lunar Soil Simulant

MLS   Minnesota Lunar Simulant
MSDS   Material Safety Data Sheet
MSFC   Marshall Space Flight Center

NASA   National Aeronautics and Space Administration
NIST   National Institute of Standards and Technology

NORCAT	Northern Centre for Advanced Technology Inc.
NVB	Napa Valley Basalt Simulant
PRM	Properties Requirements Matrix
REE	Rare-Earth Elements
RF	Radio Frequency
RLEP	Robotic Lunar Exploration Program
SBIR	Small Business Innovative Research
SEP	Solar Energetic Particles
SIMS	Secondary-Ion Mass Spectrometry
SLRS	Standard Lunar Regolith Simulant
SRC	Sample Return Container
SSAC	Simulant Science Advisory Committee
USGS	U.S. Geological Survey
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

APPENDIX B, FINDINGS AND RECOMMENDATIONS OF THE 1989 "WORKSHOP ON PRODUCTION AND USES OF SIMULATED LUNAR MATERIALS"

The 1989 Workshop report defined a lunar simulant as "*Any material manufactured from natural or synthetic terrestrial or meteoritic components for the purpose of simulating one or more physical and/or chemical properties of a lunar rock or soil.*" This definition is essentially accurate today, with an increased emphasis on root and derivative simulants and the concept of fidelity, and a decreased emphasis on the utilization of meteoritic material due to the significant expense of acquiring these materials. The primary difference, however, is the current exploration initiative that has taken simulant issues and moved them to the forefront as the need for standardized reference materials has more clearly emerged.

The 1989 Workshop recognized that lunar activities will provide access to a large resource of planetary materials that will facilitate the evolutionary extension of human presence into space, and that lunar ISRU must be developed. It was clearly recognized that lunar samples are too valuable to destructively utilize in support of these technological developments, and that terrestrial simulants must be produced for distribution to the research community.

The compositional differences between lunar and terrestrial materials were highlighted, e.g., ferric iron and hydrous phases in terrestrial materials, and reduced iron and anhydrous phases in lunar materials; the need to utilize terrestrial sources that do not contain hydrous phases and clays was emphasized. Additionally, the uniqueness of lunar materials was attributed to the diversity of lunar soil particulates such as glassy spheres, angular shards, and impact-welded agglutinates.

The properties of lunar materials that the workshop highlighted as important to simulate include size distribution, electrostatic and magnetic properties, geomechanical properties (strength, density, etc.), agglutinates with single-domain iron, chemical reactivity, bulk chemical composition, modal composition, texture, and the presence of implanted solar wind gases.

An activities-driven scenario was used, and a matrix was presented that relates these activities to the properties, starting materials, production methods, and projected amounts of simulant needed.

The compositional needs and potential terrestrial feedstocks for simulants were identified for high-Ti mare basalt, low-Ti mare basalt, KREEP basalt, ferroan anorthosite, and high-Mg anorthosite. The lunar materials and proposed terrestrial source materials are summarized in Table C.1. It was recognized that special properties could be approximated with synthetic or modified simulants (e.g., ilmenite with no Fe^{3+}) or from meteorites. The production processes identified include crushing and sieving of rocks and synthetic glasses, concentrating minerals from natural and synthetic sources, and generation of glass spheres and agglutinates. Subsequently, synthetic agglutinates were produced at the University of Minnesota by P. Weiblen.

The need for a standardized set of simulants was identified and summarized: *"By making adequate amounts of these simulants available, they will become standards through which test results can be compared. As standard properties are determined and used, the characterized database grows, making the simulants more valuable. There is an urgent need for the characterization, validation, and distribution of simulants to be linked in a coordinated way to the production of simulants. There is also a need for a dedicated NASA organization to assume responsibility for integrating these activities".*

Table B.1 Proposed Lunar Materials and Terrestrial Feedstocks (1989 Workshop)

Lunar Material	Potential Terrestrial Feedstock
1. High-Ti mare basalt	Keweenawan basalt from Duluth, MN
2. Low-Ti mare basalt	Wide variety of Keweenawan basalts, Triassic basalts from eastern U.S., Hawaiian basalts
3. KREEP basalt	Keweenawan basalt
4. Ferroan anorthosite	Anorthosites from Stillwater complex, MT
5. High-Mg anorthosite	Noritic anorthosite from Stillwater complex, MT
6. Special materials	a. Meteorites b. Synthetics (e.g., ilmenite without ferric iron) c. Ion-implanted materials d. Bulk glasses

The need to coordinate these activities was assigned to NASA; a Simulant Advisory Committee was proposed in order to have oversight responsibility for simulant development, and finally a need for a simulant curator was identified.

The key recommendations reached by the 1989 Workshop were:

1. It is strongly recommended that lunar simulant components be produced and made available to researchers as soon as possible.
2. That NASA should immediately designate a lunar simulant curator and establish a lunar simulant advisory committee.
3. Every effort should be made to assist the research community with appropriate knowledge transfer concerning the feasibility and design of specific experiments requiring simulants.

The initial production run of JSC-1 was organized subsequent to this workshop, and approximately 12,000 kg of simulant was produced and distributed.

APPENDIX C, RANKING OF LUNAR REGOLITH PROPERTIES BY CONSENSUS COUNTS AT 2005 WORKSHOP

Table C.1 Order Of Importance of Lunar Regolith Properties Based on Consensus Count by 2005 Workshop Attendees (Page 1 of 2)

Order of Importance	Lunar Regolith Property	Consensus Count
1	Grain Property/Grain Size	20
2	Grain Property/Grain Size Distribution	20
3	Physical/Particle Density	14
4	Chemical Property/Glass	14
5	Physical/Bulk Density	13
6	Modal Composition/as a Function of Grain Size	12
7	Grain Property/Grain Shape	12
8	Chemical Property/Bulk	12
9	Grain Property/Magnetic Properties	11
10	Geomechanical Property/Mechanical/Strength/Compressive	11
11	Modal Composition/Total	11
12	Geomechanical Property/Mechanical/Strength/Coefficient of Friction	10
13	Physical/Porosity	10
14	Chemical Reactivity/as Volatile/Soluble Mineral	10
15	Implanted Solar Particles	9
16	Grain Property/Grain Shape Distribution	9
17	Electrostatic Charging Property	9
18	Geomechanical Property/Mechanical/Strength/Shear	9
19	Geomechanical Property/Mechanical/Fatigue	9
20	Physical/Thermal Properties	9
21	Physical/Surface Area	9
22	Physical/Friability	9
23	Geomechanical Property/Mechanical/Strength/Grain Hardness	8

Table C.1 Order Of Importance of Lunar Regolith Properties Based on Consensus Count by 2005 Workshop Attendees (Page 2 of 2)

Order of Importance	Lunar Regolith Property	Consensus Count
24	Geomechanical Property/Mechanical/Strength/Rheology	8
25	Geomechanical Property/Mechanical/Strength/Angle of Repose	7
26	Physical/Permeability	7
27	Geomechanical Property/Mechanical/Strength/Tensile	6
28	Geomechanical Property/Mechanical/Strength/Fracture	6
29	Chemical Reactivity/From Surface Damage	5
30	Texture	4
31	Agglutinate-Specific Property/With Single Domain Iron	3
32	Geomechanical Property/Mechanical/Strength/Impact Resistance	2

APPENDIX D, 2005 WORKSHOP SESSION ATTENDEES

Mian Abbas
NASA/ Marshall Space Flight Center

David G. Agresti
University of Alabama at Birmingham

Susan Batiste
University of Colorado, Boulder

Melissa Battler
University of New Brunswick

Justin Berman
US Army Corps of Engineers - Cold
Regions Research and Environment
Laboratory

Ernest Berney
US Army Corps of Engineers –
Environment Research and Development
Center

Manojeet Bhattacharya
University of Alabama in Huntsville

Walter Boles
Middle Tennessee State Univ

Ralph W. Bruce
RWBruce Associates Inc.

Darryl Calkins
US Army Cold Regions Research and
Environment Laboratory

Paul Carpenter
BAE Systems/ Marshall Space Flight Center

Edgar Carrasquillo
NASA/Marshall Space Flight Center

James Carter
University of Texas at Dallas

Alex Chernov
BAE Systems/ Marshall Space Flight Center

Larry Clark
Lockheed Martin

Sharon Cobb
NASA

David Cole
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Regions Research and Environment
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Edwin Ethridge
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Mike Fiske
Morgan Research Corporation

Donald Frazier
NASA/Marshall Space Flight Center

Raymond French
NASA/ Marshall Space Flight Center

Scott Gilley
Tec-Masters, Inc.

Marty Gustafson
Orbital Technologies Corp.

Buddy Guynes
NASA/ Marshall Space Flight Center

Alberto Hernandez
University of Alabama in Huntsville

Alex Ignatiev
University of Houston

William Kaukler
University of Alabama in Huntsville

Russell Kerschmann
NASA - Ames Research Center

Gerald Kulcinski
University of Wisconsin

Gary Lofgren
NASA – Johnson Space Center

David Lynch
University of Arizona

Trygve Magelssen
Futron Corporation

David McKay
NASA/Johnson Space Center

Gregory Meeker
US Geological Survey

Masami Nakagawa
Colorado School of Mines

Chuck Owens
Teledyne Brown Engineering/ Marshall
Space Flight Center

Narayanan Ramachandran
BAE Systems/ Marshall Space Flight Center

Chandra Ray
NASA/Marshall Space Flight Center

Ramana Reddy
The University of Alabama

Doug Ryckman
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Kris Romig
NASA/ Johnson Space Center

Kurt Sacksteder
NASA/Glenn Research Center

Donald Sadoway
Massachusetts Institute of Technology

Ronald Schlagheck
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Subhay Sen
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Laurent Sibille
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Thomas Simon
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Louise Strutzenberg
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Lawrence Taylor
University of Tennessee

Sam Toutanji
University of Alabama in Huntsville

Sandra Wagner
NASA/ Johnson Space Center

Stephen Wilson
U.S. Geological Survey

APPENDIX E, GLOSSARY

Agglutinate -

A fragile, irregularly shaped particle composed of lithic, mineral, and glass fragments welded together by glass splashes from micrometeorite impacts. Agglutinates are usually less than 1-2 mm diameter. Since micrometeorite impacts affect only the uppermost soil grains, agglutinates are an indicator of surface exposure, or maturity. They also contain implanted solar wind gases such as hydrogen.

Angle of Repose -

The maximum angle of slope, measured from horizontal, at which loose, cohesionless material will come to rest on a pile of similar material. The terrestrial angle of repose commonly ranges from 33° to 37°.

Anorthosite -

A plutonic rock composed almost entirely of plagioclase feldspar. Plagioclase in terrestrial anorthosite ranges from sodic andesine to calcic bytownite. However, the lunar anorthosite is nearly calcic plagioclase anorthite ($CaAl_2Si_2O_8$) with compositions close to An_{95}.

Basalt –

A dark, fine-grained, extrusive (volcanic) igneous rock with a low silica content (40% to 50%), but rich in iron, magnesium and calcium. Generally occurs in lava flows, but also as igneous intrusions known as dikes. This term is used to denote both compositional and textural information.

Beneficiation –

Processes that take an unsorted and unclassified raw material and produce a product that is sorted on one or more properties, such as size or modal mineralogy, as input for subsequent processes.

Breccia –

Rock that consists of coarser fragments or clasts of rock, mineral, or glass, enclosed or contained in a matrix that is of a finer grain size and may be of similar or different material. The conversion from soil to rock depends on the degree of lithification.

Bulk density -

Mass of a material divided by its volume, including the volume of pore spaces. The in situ bulk density of lunar soils, as measured in Apollo core samples, ranges from 1.4 to 1.9 g/cm^3.

Bulk grade –

Those simulants that could be used for scientific and engineering testing where the process under consideration depends primarily on the physical properties of the simulant, with significantly reduced dependence on chemical and mineralogical properties.

Cohesion -

Shear strength in a sediment not related to interparticle friction.

Compressive strength - The maximum compressive stress that can be applied to a material before failure occurs.

Contingency sample – Lunar material sample collected and stored during Apollo surface missions in the event of a shortened mission.

Crustal – Term referring to materials from the outermost structural layer of the Earth or Moon. The crust of the Earth is generally composed of granitic materials on the continents and basaltic materials in the oceans. The crust of the Moon is composed of anorthositic materials in the highlands and basaltic materials in the maria.

Derivative simulant – Simulant obtained through processing of a root simulant to achieve a simulant of specific properties. Such simulants may contain additive components such as microspherical glass, synthetic agglutinates, solar wind implanted gases, nanophase iron, soil-ice mixtures, and vapor-coated grains.

Devitrification - Conversion of the glassy texture of a rock to a crystalline texture after solidification.

Downhole - The term downhole is used to describe tools, equipment and instrumentation which are used in the wellbore. Downhole can also be applied to the conditions or techniques applying to the well.

Dust Simulant – Terrestrial material used to replicate the fine size fraction of the lunar regolith (i.e., 50 μm particle size).

Family – A group of simulants with similar characteristics and features.

Fatigue - Failure of a material after many repetitions of a stress that of itself is not strong enough to cause failure.

Ferric iron - Iron in the +3 oxidation state (Fe^{3+}); an iron atom that has lost 3 electrons, resulting in a +3 electrical charge.

Ferroan anorthosite - The mafic minerals in the ferroan anorthosite are relatively enriched in Fe compared to high-Mg anorthosites. The ferroan anorthosites are more abundant Moon-wide. A simulant for lunar ferroan anorthosite may be found in the Stillwater complex, Montana, a layered intrusion that also contains an analog for high-Mg anorthosite

Fidelity – (degree of) Describes the degree of accuracy with which a simulant material approximates the properties of planetary material. Used in this report in the context of lunar simulant.

Friable - Easily broken or reduced to a powder (applied to rock or mineral).

Glass reduction - Processing of the metal oxide component of the glassy part of lunar soil. A reducing agent such as H_2 or C is used to form an intermediate compound, which can then be further processed to release O_2.

High-Mg anorthosite - The mafic minerals in the high-Mg anorthosite are relatively enriched in Mg compared to ferroan anorthosites. A simulant for lunar high-Mg anorthosite may be found in the Stillwater complex, Montana, a layered intrusion that also contains an analog for ferroan anorthosite.

High-Ti mare basalt - Lunar mare basalts that contain $> 9\%$ TiO_2 are classified as high-Ti mare basalts.

Highlands - The light-colored, older, more cratered lunar terrain at higher elevation, which is relatively enriched in calcium and aluminum. These regions are characterized by a higher albedo than the Mare regions of lower elevations. They comprise 80% of the lunar surface. The highlands are thought to be composed predominately of anorthosite.

Hydrous phases - Mineral phases formed as a result of reaction with water.

Ilmenite - This iron-black mineral is the most abundant opaque mineral found in lunar rocks, mostly in mare basalts, and with compositions near $FeTiO_3$. Most lunar ilmenite contains some Mg (zero to 5-6% MgO by weight). Although terrestrial ilmenite almost always contains some Fe^{3+}, lunar ilmenite contains none. Reduction of this mineral is being studied to produce oxygen (see ilmenite reduction).

Ilmenite reduction - A method of extracting oxygen from the mineral ilmenite ($FeTiO_3$). A reducing agent such as H_2, C, etc. is reacted with the mineral to form H_2O or CO, etc., which can then be separated (by electrolysis, for example) into oxygen and reductant, after which the reductant is recycled to be used in the process again.

Immature - Characteristic of a soil that has been exposed on the uppermost lunar surface for a relatively short time (see Maturity).

Implanted solar particle - Atomic nuclei from the sun (see Solar flare and Solar wind) that impinge on grains with enough energy to become implanted in the grain surface. The most common nucleon is hydrogen, but other useful volatiles such as He, C, and N are also implanted.

ISSP - Acronym for in-flight sustained shockwave plasma. An ISSP reactor at the University of Minnesota consists of a hollow, central cathode radially surrounded by six anodes. Arc rotation of 1000-3000 rpm maintains the shockwave plasma in a rotating, homogeneous magnetic field. Crushed rock is injected in the plasma and partially melted, forming agglutinate-like products and other glasses.

KREEP -   Acronym for potassium (K), rare earth elements (REE), and phosphorus (P). These elements are relatively enriched in the Fra Mauro region (Apollo 14 site) of the Moon. KREEP-rich basalts are also enriched in uranium and thorium and believed to be the last chemical remnants of the lunar magma ocean after the lunar crust formed.

Lithology -   The physical character (color, structure, mineralogy, and grain size) of a rock.

Low-Ti mare basalt -   Lunar mare basalts that contain 1.5 to 9% TiO_2 are classified as low-Ti mare basalts. See also high-Ti mare basalt and very low-Ti mare basalt.

Lunar Dust –   The fine size fraction of the lunar regolith with grain size below 50 μm.

Lunar simulant -   Any material manufactured from natural or synthetic terrestrial or meteoritic components for the purpose of simulating one or more physical and/or chemical properties of a lunar rock or soil.

Mare -   (Plural: maria) The dark colored, younger, less cratered lunar terrain at lower elevation, that is relatively enriched in iron and magnesium. It was formed by basaltic flows during volcanic periods of lunar history and exhibits a lower albedo than the surrounding highlands. They comprise approximately 20% of the lunar surface.

Mature -   Characteristic of a soil that has been exposed on the uppermost lunar surface for a relatively long time (see Maturity).

Maturity -   Relative length of exposure time of soil grains on uppermost lunar surface. While on the surface, grains are exposed to micrometeorite impacts and solar wind and solar flares (see solar wind and solar flare). Thus, indicators of soil maturity include (I) the concentration of single-domain metallic iron (see nanophase Fe), (2) abundance of agglutinates, and (3) the concentration of implanted solar gases such as H and He.

Megaregolith –   First coined by W. K Hartman to describe that part of the lunar crust that has a variable thickness of up to several kilometers, sandwiched between the surface thin regolith layer of a few meters in thickness and the bedrock below (Lunar Sourcebook, pp. 92 and 286). This layer of fractured bedrock may consist of large (greater than 1 m) blocks. Some of the inferred properties are different from those of the unconsolidated surficial material that has been sampled by the Apollo missions.

Modal composition -   The mineral abundances in a rock or soil, usually expressed in weight or volume percentages. Also referred to as the mode.

Monomict -   Breccias which are composed of a single rock type of differing sizes.

Nanophase Fe -   In lunar regolith particles, single-domain nanophase iron is descriptive of the nanophase metallic iron grains dispersed throughout the glassy phases produced by micrometeorite impacts in the presence of implanted solar protons.

Olivine -   A silicate mineral that displays a solid solution series between Mg_2SiO_4 (Forsterite) and Fe_2SiO_4 (Fayalite).

Oxygen fugacity (fO_2) –   The partial pressure of oxygen. Parameter describing relative reducing or oxidizing conditions in geochemistry, based on the chemical potential of oxygen in a given environment. Oxygen fugacity is a measure of the amount of free or uncombined oxygen that is available in an environment. High fO_2 describes oxidizing conditions and low fO_2 describe reducing conditions.

Permeability -   Capacity of a porous rock or soil for transmitting a fluid (gas or liquid).

Plagioclase -   A feldspar mineral which displays a solid solution series between $NaAlSi_3O_8$ (albite, abbreviated Ab) and $CaAl_2Si_2O_8$ (anorthite, abbreviated An). Compared to terrestrial plagioclases, the lunar plagioclases are more calcic and less diverse. Plagioclase found in mare regions ranges from 74 to 98 mole % An compared to Ab. Highland plagioclases are more calcic, ranging from % An 90 to 99. Most of the white material observed in lunar rocks is plagioclase.

Polymict –   Breccias which are composed of rocks from different sources.

Porosity -   Percentage of the bulk volume of a rock or soil occupied by interstices.

Pristine -   Lunar highlands samples that have the highest Mg/Fe ratios and Ca/Na ratios, and so are distinct in terms of their bulk and mineral chemistry.

Pyroclastic -   Pertaining to clastic rock material formed by volcanic explosion. Lunar pyroclastic deposits often consist of glass spheres, thought to be formed in a fire fountain.

Pyroxene -   A group of silicate minerals having the general formula $ABSi_2O_6$ where A= Ca, Na, Mg, or Fe^{2+} and B= Mg, Fe^{2+}, Fe^{3+}, Cr, Mn, or Al, with Si partly replaced by Al.

Regolith -	The layer or mantle of fragmental, incoherent, unconsolidated rocky material that overlies bedrock. This layer is considered to be 4 to 5 m thick in the mare regions, but may average about 10 to 15 m in older highland regions. The regolith layer overlies the material referred to as megaregolith.
Research grade –	This term is used to denote the highest fidelity of SLRS materials that would most closely duplicate the lunar regolith. Detailed specifications for research grade simulant materials will be defined in the NASA simulant requirements documentation.
Rheology -	Deformation and flow of matter.
Root simulant –	Term introduced by James Carter of the University of Texas – Dallas to describe the collection and development of basic materials for the development of simulant materials for the Moon and eventually Mars. Basic root stimulants will be useful for many purposes including the development and testing of a variety of planetary surface systems. Derivative simulants (branches from the root) can be derived from the root simulant. These derived simulants may contain microspherical glass, synthetic agglutinates, solar wind implanted gases, nanophase metallic iron, soil-ice mixtures, and vapor-coated grains.
Shear strength -	Resistance of a body to shear stress.
Simulant-	See Lunar simulant
Soil -	Lunar soil is the portion of the regolith having grains < 1 cm in size.
Solar flare -	Nuclei sporadically ejected from the Sun that strike the lunar surface at with energies of 1-100 MeV per nucleon and penetrate about l mm into regolith grains. Nuclei in the iron group ($Z = 18$ to 28) can leave tracks in silicates. The solar flare proton flux striking the Moon averaged for those protons > 10 MeV over 1 m.y. is about 100 per cm^2 per sec.
Solar wind -	Nuclei, mostly protons (hydrogen), with -10% alpha particles (helium), ejected from the Sun that strike the lunar surface at approximately 1 KeV per nucleon and penetrate only approximately 100 Å into regolith grains. The proton flux is about 108 per cm^2 per sec.

Surface area -
The area of the outer surface of grains. For a bulk particulate solid, surface area increases as grain size decreases. Grain shape, pore size, and chemical activity are also factors. Quantitative values for surface area vary with the method used to measure it (a matter of scale). Methods that measure particle or pore size cannot be compared with surface areas measured by the amount of gas that can be absorbed as a monolayer.

Technical grade –
Simulant materials developed for a more general use such as excavation and drilling. Systems requiring this type of simulant material may not have or need the high fidelity required of a volatile extraction experiment.

Tensile strength -
Maximum applied tensile stress that a body can withstand before failure. Tensile stress is the stress that tends to pull a body apart.

Titanomagnetite –
Mineral solid solution series between magnetite Fe_3O_4 and ulvospinel Fe_2TiO_4. These compositions represent variable amount of Fe^{3+} in the magnetite component, and are present only in terrestrial materials.

Trafficability –
The ability of a soil to support a vehicle and to provide traction for movement. ☺

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